University of Minho
School of engineering

Francisco Fernandes Mikus

Material Flow Analysis applied to batteries with a circular economy perspective

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Professora Doutora Paula Fernanda Varandas Ferreira

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I would like to dedicate this work to my family, especially to my parents, my brother, and my sister, who supported me throughout my academic studies.

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Furthermore, I thank my colleague and friend Marcela who provided me with her precious help.

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Statement of Integrity

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July 2024

Francisco Fernandes Mikus

Abstract

Material Flow Analysis applied to batteries with a circular economy perspective

In this research, a material flow analysis is developed for lithium-ion batteries of electric vehicles in the Czech Republic alongside three different scenarios of circularity. The aim of this work is to find circular solutions to the management of this technology at its end of life and understand the positive and negative impacts of its utilization. This study is very relevant in today's energy transition since electric vehicles are gaining popularity and are the main solution for the decarbonization of the transport sector, which is one of the sectors that most release carbon dioxide and other greenhouse gases into the atmosphere, contributing to the climate change faced today. Nevertheless, this technology can also present some challenges to sustainability since it requires the exploitation of some critical material that can harm ecosystems and result in public health issues, so it is crucial to understand how to manage this technology in its lifecycle. Initially, the number of electric vehicles that entered the Czech Republic market is estimated, and then the several features and characteristics of this technology are studied so the desired results are achieved. The quantity of different materials that constitute batteries that finish their useful life in electric vehicles is calculated, and from that, the amount of material reused, recycled, and disposed of is determined. These results are interpreted and challenges and limitations are highlighted.

Keywords

Circular Economy, Czech Republic, Lithium-ion batteries, Material Flow Analysis

Resumo

Análise do fluxo de materiais aplicada a baterias numa perspetiva de economia circular

Nesta investigação, é desenvolvida uma Análise do Fluxo de Materiais para as baterias de iões de lítio de veículos eléctricos na República Checa, em três cenários diferentes de circularidade. O objetivo deste trabalho é encontrar soluções de circularidade para a gestão desta tecnologia no seu fim de vida e compreender os impactos positivos e negativos da sua utilização. Este estudo é muito relevante na transição energética atual, uma vez que os veículos eléctricos estão a ganhar popularidade e são a principal solução para a descarbonização do sector dos transportes, que é um dos sectores que mais liberta dióxido de carbono e outros gases com efeito de estufa para a atmosfera, contribuindo para as alterações climáticas que se verificam atualmente. No entanto, esta tecnologia pode também apresentar alguns desafios à sustentabilidade, uma vez que requer a exploração de alguns materiais críticos que podem prejudicar os ecossistemas e resultar em problemas de saúde pública, pelo que é crucial compreender como gerir esta tecnologia no seu ciclo de vida.

Inicialmente, é estimado o número de veículos eléctricos que entraram no mercado da República Checa e, em seguida, são estudadas as várias características desta tecnologia, que permitem obter os resultados desejados. É calculada a quantidade de diferentes materiais que constituem as baterias que terminam a sua vida útil nos veículos eléctricos e, a partir daí, é determinada a quantidade de material reutilizado, reciclado e eliminado. Estes resultados são interpretados e os desafios e limitações do trabalho identificados.

Palavras-Chave

Análise do Fluxo de Materiais, Baterias de iões de lítio, Economia Circular, República Checa

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List of abbreviations

CO2 – Carbon dioxide

LIB – Lithium-ion batteries

EV – Electric Vehicle

ESS – Energy Storage Systems

EC – Electronic Components

EoL – End of Life

MFA – Material Flow Analysis

CZ – Czech Republic

GHG – Greenhouse Gases

NECP – National Energy and Climate Plan

LDV – Light-duty vehicles

HDV – Heavy-duty vehicles

LMO - Lithium Manganese Oxide

NCA – Lithium Nickel Cobalt Aluminium Oxide

NMC – Lithium Nickel Cobalt Manganese Oxide

LFP - Lithium Iron Phosphate

Li – Lithium

Co – Cobalt

Ni – Nickel

Mn – Manganese

Al – Aluminium

Fe - Iron

P – Phosphorus

Cu – Copper

Gr – Graphite

STAN – Substance Flow Analysis

1 Introduction

In these past years, several countries have been focusing on decarbonizing the various sectors with the aim of reducing the increasing presence of carbon dioxide (CO2) and other greenhouse gases (GHG) in the atmosphere, so the way how to produce energy both for industrial and domestic consumption and in transportation has suffered several changes in these past decades. In this period of energy transition where non-renewable energies such as fossil fuels are being replaced with renewable and innovative sources of energy, batteries play a crucial role since they are used in several technologies such as electric vehicle (EV), energy storage systems (ESS) and electronic components (EC) (Peters et al., 2021). Nonetheless, with the increasing use of batteries, it is important to understand how to handle them when they reach End of Life (EOL) since batteries contain metals such as lithium (Li), nickel (Ni), and cobalt (Co) that not only can create damage to ecosystems when disposed of Bandh et al., (2023), but they also represent a threat to human health, as Liu et al., (2021) mentions, that cobalt and nickel in lithium-ion batteries (LIB) are classified as carcinogenic, mutagenic, and toxic to human reproduction. For this reason, LIB need to be well managed once they reach EOL. It would not make sense to engage in an energy transition to protect the planet when the solutions applied would harm it in another way. Therefore, the use of batteries in these new sources of energy must be done in a sustainable way, and this is where the concept of circular economy comes in. Sustainable business models that follow this concept focus on the efficiency and circularity of products and materials in all systems, being the main goal of achieving a prosperous, stable, and sustainable future where humans live in syntony with the environment and the planet.

In this research, a material flow analysis (MFA) will be developed for LIB materials for Electric Vehicles in the Czech Republic (CZ). This analysis will be conducted from the stage of batteries' use to the collection and management stage, so the number of different materials that compose batteries entering the end of life, the amount that is reused and recycled, and the amount that is disposed of are quantified. Lithium-ion batteries are a technology in constant development so some changes in their attributes and composition have been occurring over the years. For this reason, it is important to explain the variables used and the assumptions made. By the end of the work, results will be discussed and evaluated with a circular economy perspective with the aim of understanding how to manage batteries in EoL.

1.1 Methodology

The MFA applied to LIB from EV will be addressed to the CZ since, for the reasons explained later in this work in the literature review, it is a country with an increasing tendency of EV sales with these batteries. This is due to the fact that the country is committed to its decarbonization goals, which are in line with the ones from the European Union (EU). With these goals, both the CZ and the EU are committed to solving the challenges faced today with climate change. After studying in detail the novelty of LIB and the selected market of the CZ, a quantitative approach (the MFA) will be studied with information collected from scientific literature and official reports.

To complete the MFA, it was used the software Substance Flow Analysis (STAN) which was developed at the Research Unit for Waste and Resource Management at Technische Universitat Wien and it enables the building of graphical models by using predefined components such as processes, flows, system boundaries, and others. Data regarding different materials studied in a MFA are inputted and the software computes unknown quantities and displays, in a Sankey diagram, all flows of the analysed product for a specific period. Not only is recommended by the Austrian standard ÖNorm S 2096 Stan2web, (n.d.) but also widely used by the scientific community for waste management (Cencic & Rechberger, 2008). Note that this software is not able to make a dynamic MFA (it does not consider stocks and flows from one year to the next). Therefore, calculations must be carried out in Excel and then the accumulated amount of material regarding all years studied is inserted in the software.

Besides being simple and intuitive the use of STAN presents several advantages such as:

- It follows the principle of mass conservation, where the sum of all inputs must be exactly equal to the sum of all outputs, avoiding this way errors.
- It respects the principle of linear relation making it easier to fill out the model.
- It uses mathematical statistical tools such as data reconciliation, error propagation, and gross error detection verifying the accuracy and validation of the data, and uncertainty propagation.

The necessary data is collected from previous research, reports of organizations such as the International Energy Agency (IEA) and World Economic Forum (WEF), and platforms like Cista Doprava which is under the jurisdiction of the Ministry of Transport of the CZ. The data is gathered and managed in the interface Microsoft Excel and then applied in the software STAN.

Even though there are a lot of different battery technologies in use in the market, this research focuses on and applies a MFA to lithium-ion batteries since it is a well-established technology, meaning that there is a solid understanding of its characteristics and ample experience in its large-scale manufacturing. Also, the demand for these batteries has grown in recent years with the increasing use of EVs. According to the International Energy Agency, in 2022, demand for lithium-ion batteries in the automotive sector increased by around 65% to reach 550 GWh, up from 330 GWh in 2021 (IEA, 2023). Alternative technologies are still at a range of lower technology readiness levels (TRLs), and it takes time to develop and mature them (IEA et al., 2020). For this reason, in future years there will be an increasing number of lithium-ion batteries from EVs reaching EoL, therefore it is crucial to find solutions to its management. In this research, the LIB and their materials will be quantified for the country of the CZ because, as stated earlier, it is one of the countries with an expected growth in the number of EV sales in the coming years, in order to achieve its emission reduction targets.

1.2 Research goals and research question

This work intends to identify the problems that the use of lithium-ion batteries presents to the environment and to find solutions that promote the circularity of materials that constitute lithium-ion batteries, so three specific goals are established. First, to estimate and characterize the batteries reaching EoL in CZ in the period studied. Second, to determine in which proportion the materials could be recycled and reused in a second life in different scenarios (some following circular economy concepts and others linear ones). Third, to estimate the benefits of applying circular solutions on LIB. After defining the goals, the research question is stated:

RQ: How can circular waste management support the sustainability of lithium-ion batteries?

1.3 Structure of the research

The research is structured as follows. Chapter 1 explains the importance of doing a MFA of batteries at a time when they play a crucial role in the energy transition. Goals are defined and the research question identified, which is expected to be answered by the end of the work. Then, in Chapter 2 a literature review is developed so it can support the work and provide a better understanding of the topic, starting with the definition of circular economy and its contextualization in the energy sector, and continuing with presenting the framework of the CZ including its decarbonization plans, comparing with the targets set by the European union with the green deal, the country's engagement with the energy transition, EVs and clean mobility, and the battery recycling regulation

in the country and the EU. To conclude in the literature review the technology behind LIB is explained. In chapter 3 a MFA is developed for the LIB system in the CZ. First, the space and time boundaries of the research are defined, and the system model made in the software STAN is presented where it is possible to see the various processes and flows of all LIB's life cycle. Then, variables, assumptions, and scenarios are explained. Chapter 4 discusses the results of the MFA within a circular economy perspective and some solutions for the correct management of batteries in EoL are suggested. To complete the research, in chapter 5 conclusions are made and the research question is answered.

2 Literature review

In this chapter, a literature review is made so it can complement the MFA with the theory regarding the topics discussed. First, the concept of circular economy and its role in the energy transition is presented. Secondly, the Czech Republic's framework concerning its decarbonization plans and targets, the country's commitment to electric vehicles, and recycling legislation in the EU are presented. Lastly, since lithium-ion batteries are a complex technology, it is also studied their background, evolution, characteristics, and current status of waste management.

2.1 Circular Economy

The circular economy is a model of production and consumption wherein the materials are managed in a way to minimize waste, and products are designed to be reused and recycled (Li & Xu, 2022). Material's circularity and efficient use of resources are present in this concept which has been gaining interest from scholars, institutions, companies, and governments that are committed to finding solutions to the problems faced with climate change. It is important to understand that this model is not only based on reusing and recycling but also on other R's which include Reducing, Reusing, Recycling, Repurposing, Remanufacturing, and Rethinking according to (Bandh et al., 2023). Daphne, (2023) takes the concept even further and explains that there are 10 R's to consider in the different stages of resource use and waste management. The author divides these R's into three categories. The first category focuses on smarter product use and manufacture and includes Refuse, Rethink, and Reduce. The second category focuses on product life extension and consists of Reuse, Repair, Refurbish, Remanufacture, and Re-purpose. Lastly the third category on Recycle and Recovery of materials. Therefore, in a circular economy all stages in the lifecycle of materials, from raw material to product in EoL are interconnected and designed in a way that waste is minimized, and efficiency prevails. Figure 1 demonstrates the interconnections of several stages and processes in a product lifecycle in a circular economy.

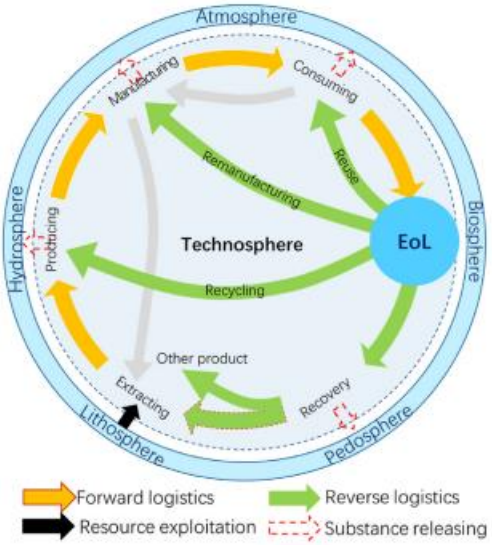


Figure 1: Circular economy linking forward and reverse logistics towards circularity (Zeng et al., 2022)

Gunter Pauli, in his book "*The Blue Economy*", raises the bar even higher by considering that an economy based on nature's genius, where innovations emulate natural systems, is the solution to achieving a sustainable future at an environmental, social, and economic level. In this model, not only the circular economy is present, but also the inspiration of nature's creativity, adaptation, and abundance in innovations that create several benefits such as food security, multiple revenue streams, jobs, and conservation and regeneration of ecosystems (Pauli, 2010).

2.1.1 From linear to circular economy

In a linear economy, raw materials are extracted, then taken to production, and after use, they are disposed of and not recovered. Adopting this traditional linear flow of materials is known as an extract-manufacture-use-dispose economy (Zeng & Li, 2021). Bandh et al., (2023) argue that more than 90 billion tons of raw materials were fed into the linear system of manufacturing in 2020, depleting the limited natural sources that the planet Earth offers, including non-renewable energies, and returning to it hazardous waste. This linear model causes and has caused environmental disasters such as biodiversity loss and polluted ecosystems, as well as considerable negative human health repercussions. According to Johansson, (2021), just the processes of extraction and processing of natural resources account for more than 90% of global biodiversity losses and water stress, 50% of climate emissions, and one-third of the health effects of particulates. On the other hand, in a circular economy, the materials extracted from nature remain in the economy for a longer time and the loss of material to nature is lower. Secondary materials are acquired with recycling, satisfying this way, part of the demand for new materials.

As stated in the previous section, interest by entities in moving from a linear to a circular economy is growing, and in March 2020 the European Union adopted a new circular economy action plan (CEAP), one of the pillars of the European Green Deal. In this plan, the EU sets several goals for the circularity of products, namely for electronics, packaging, plastics, textiles, construction and buildings, food, water, batteries, and vehicles (European Commission, 2020).

2.1.2 Circular Economy in the energy transition

The energy transition is a complex process in which changes to energy technologies, and social and economic aspects of energy production and consumption occur (Gladkykh et al., 2024). In this process, there is a gradual change in the sources used to produce energy, and specifically, in the energy transition faced today, fossil fuels have been replaced with renewable and clean sources, with the main goal of decarbonizing the energy sector and, in this way, eliminating the emissions of CO2 and other GHG. The European Union shows great concern about this and has established with the Green Deal several goals, like achieving carbon neutrality by 2050, and it also plans to review the regulation of the European energy network by incorporating smart technologies, smart grids, hydrogen, and other renewable energies (Fetting, 2020).

However, the transition to these new sources of energy brings other concerns, such as the extraction of raw materials necessary for producing and maintaining technologies like solar panels (photovoltaic), wind turbines (Eolic), and batteries (ESS and EV). Bandh et al., (2023) estimate that waste generated from renewable energies will increase up to 30 times in the next 10 years. That is why the circular economy is the solution to the obstacles that energy transition presents, since with recycling and recovery of materials at the end of life, it is possible to offer secondary materials for production and reduce the dependence on extracting new materials. Additionally, this approach embraces the use of goods in second life, for example, the use of batteries from EVs in ESS, as Moore et al., (2020) explain. Other CE tools allow circularity of materials and efficient use of goods.

In the Green Deal, one of the key areas is mobilizing industry for a circular economy, and the European Commission plans a set of recommendations especially for high-energy-intensive industries Fetting, (2020), so it helps the industry to move forward in the right direction in an energy transition aligned with the circular economy.

2.2 Czech Republic Framework

The MFA in this research is developed in the context of the CZ, so first, it is essential to understand the position of the country in the energy transition, including its decarbonization plans and targets.

Next, the position of CZ with EVs is interpreted, and the importance of these vehicles in the decarbonization plans of the country is explained. CZ is also the founder and main producer of Škoda, a brand of cars very popular in the country and around the world, so the company's position regarding clean mobility is analysed. Lastly, in this chapter, the current recycling and EoL management framework of CZ and the EU regarding batteries is displayed.

2.2.1 Decarbonization plans and targets

The CZ defines its targets to reach carbon neutrality in accordance with the European Union since it is a member state. The country makes its own strategy for the years to come but with the goal of achieving the targets set by the EU. The country elaborated the National Energy and Climate Plan (NECP) in 2019, and in October 2023, approved an update to this plan with more ambitious targets, as the EU also increased its initial targets. Initially, it is stated in the NECP that the EU has set a target to achieve a Greenhouse Gas (GHG) reduction of at least 40% by 2030 compared to 1990, and an emission reduction in the EU Emission Trading System (ETS)[1] and non-ETS[2] sectors by 43 % and 30 %, respectively, compared to 2005 (Czech Republic Government, 2019). The targets initially defined are shown in Table 1.

Table 1: EU and CZ targets before the Green Deal. Information gathered from NECP

	Before the Green Deal			
	GHG emission reduction by 2030 compared to 1990	GHG emission reduction by 2050 compared to 1990	Emission reduction by 2030 in ETS sectors compared to 2005	Emission reduction by 2030 in non-ETS sectors compared to 2005
EU Targets	40%	80%	43%	30%
CZ Targets	40%	80%	not applicable	14%

The Ministry of the Environment of the CZ adopted the Climate Protection Policy Zámyslický et al., (2017), where it established the following objectives for reducing GHG emissions:

- Target for 2030, to reduce national emissions by at least 44 Mt CO2 equivalent compared to 146 Mt of CO2 equivalent emissions in 2005.
- Target for 2050, to pursue the indicative level of 39Mt CO2 equivalent of emissions.

[1] ETS is a carbon market part of the EU's policy to combat climate change and reduce GHG emissions, and covers power plants, industry factories and the aviation sector (European Commission, n.d.).

[2] Non-ETS represent the sectors not covered by the EU such as transportation, agriculture, waste.

It is important to note that the target for 2050 of 39Mt CO2 eq. would correspond to a reduction of 80% GHG emissions.

According to the Czech Republic Government, (2023) the draft update of the Czech Republic's NECP, updates in the regulations by the European Parliament and of the Council were made and the country is developing the update to their plan and is planning to submit the final version on 30 June 2024. In this draft, it is stated that the target increased to a 55% reduction of GHG emissions by 2030 compared to 1990 (Fit to 55 package) and that carbon neutrality is to be achieved by 2050. This increment to the targets was also based on the Green Deal that in the meantime, had been developed in December 2019. Moreover, the targets, for the emission reduction by 2030 compared to 2005, in EU Emission Trading System (ETS) and non-ETS sectors increased from 43% to 62%, and 30% to 40% respectively. Besides that, the regulation of the European Commission establishes national targets for each state for non-ETS sectors, and initially, the target for the CZ was a reduction in the emissions of 14% by 2030 compared to 2005, and with the update this target suffered a significant increase to 26%. The targets defined after the Green Deal and the updates to the regulations are presented in Table 2.

Table 2: EU and CZ Targets after the Green Deal. Information gathered from the update of the NECP

	After the Green Deal			
	GHG emission reduction by 2030 compared to 1990	GHG emission reduction by 2050 compared to 1990	Emission reduction by 2030 in ETS sectors compared to 2005	Emission reduction by 2030 in non-ETS sectors compared to 2005
EU Targets	55%	carbon neutrality	62%	40%
CZ Targets	55%	carbon neutrality	not applicable	26%

Regarding the country's targets for the share of RES (Renewable Energy Sources), in 2019 with the NECP, the CZ has set a target of 22 % share of RES in gross final consumption by 2030. This market share would be the national contribution to reach the 32% target of the EU. However, CZ is increasing this target to 30% since the EU target for the share of RES in final consumption by 2030 increased to 42.5 %, and also because additional measures were introduced. Note that since the update of the NECP is still to be finalized the legislation was still not adopted. However, the Electricity Maps, (2024) shows that the electricity produced by renewables in the country was only 10% in 2017, 2018, and 2019, 11% in 2020, 2021, and 2022, and 12% in 2023, which demonstrates little evolution over the past years. If the country intends to achieve the target of 30% share of renewable energies, it needs to accelerate this transition.

2.2.2 Electric Vehicle in the Czech Republic

EVs play a crucial role in the energy transition since the transport sector is one of the sectors that most releases CO2 and other GHG into the atmosphere. According to Stanislaus et al., (2019) the transport sector contributes with around 16% of global GHG emissions and batteries directly avoid 0.4 Gt of CO2 emissions in this sector. The CZ has seen a slower adoption of these vehicles compared to other states in the EU and the Czech Republic Government, (2022) admits that there is a lack of EVs in the market and a lack of support from the state to motivate individuals to purchase these vehicles, in contrast with other countries that for example offer subsidies for EV purchases. Nevertheless, the CZ established in the National Action Plan for Clean Mobility (NAP CM) targets for EV annual sales shown in the following Table 3 (Ministry of Industry and Trade, 2015). In this plan, it is also emphasized that the EU with the Europe 2020 Strategy addressed the use of alternative fuel sectors to promote the transition to a low carbon economy, and specifically in the transport sector to modernize transport to reduce carbon production.

Table 3: CZ Targets for EV sales. Information gathered from NAP CM

	EV annual sales	EV in operation by the end of each period
2021-2025	25000	35 000
2026-2030	44000	250 000
After 2030	50000	400 000

The historical EV sales in CZ mirror the poor interest of the country in purchasing EVs in the past and will be explored in the MFA. Moreover, the targets presented for future EV sales are also important for the MFA of this research when predicting the future and expected sales of these vehicles in the country. As mentioned before, CZ is the home country of Škoda, an automotive company currently under the Volkswagen Group. Until now Škoda sold in the CZ only two different models of electric vehicles named Citigo and Enyaq, and the company later developed another model of Enyaq named Enyaq Coupé. Citigo is no longer for sale in the market. Nevertheless, the company plans to release 6 other models of EVs including Elroq in 2024, as mentioned in their 2023 annual report, and increase the share of EVs in Europe to more than 70% by 2030 (Škoda Auto a.s., 2024). Moreover, the company is producing its batteries in its main plant in Mladá Boleslav, and by April 2023 it had manufactured 500,000 battery systems for all-electric and hybrid vehicles (Škoda Storyboard, 2023). The company on its official website recognizes that the ideal lifecycle of batteries would be production, use, second life, and recycling so their commitment to

sustainability and clean mobility is clear. Therefore, considering Škoda's commitment, the fact that it is the most popular car in the country, and the decarbonization targets of the country, it is clear that EV sales in the CZ are expected to grow in future years, so it is important to understand how to manage LIB reaching their EoL in the years to come in the CZ.

2.2.3 Czech Republic legal and battery recycling framework

In the National Reform Program of the CZ in 2022 the Czech Republic Government, (2022) recognizes the importance of building recycling infrastructure and encouraging businesses to invest in circular solutions. Also, in the National Plan for Clean Mobility, the Ministry of Industry and Trade, (2015), explains the EU legislative framework for clean mobility, including the Directive 2000/53/EC on end-of-life vehicles. This directive aims to promote recycling, reuse, and recovery of EoL vehicles and limits European vehicle manufacturers from using hazardous materials. Also, the directive requires the design of vehicles to facilitate reuse, recovery, and recycling, and the use of recycled material. Moreover, Zhao et al., (2021) explain that according to other EU legislation, the Directive 2006/66/EC, each country of the EU must achieve a 45% collection rate and at least 50 wt % (weight percentage) recycling efficiency for non-lead acid and non-nickel cadmium batteries. The authors also state that other EU Battery Directive regulations require battery producers to pay for the collection, treatment, recycling, and disposal of waste batteries in proportion to their market share.

2.3 Lithium-ion batteries

Batteries have been used for a long time for several different purposes such as EC, ESS, and more recently for electric vehicles. It is a very complex technology, and Zhao et al., (2021) clarify that they can be classified into primary (single-use) and secondary (rechargeable). Commercially, they are classified by chemistry type such as alkaline, mercury, lead-acid, nickel-based, and lithium-based where the latter three types accounted for 94,8% of the global battery market in 2016. This work is focused on Lithium-ion batteries, as already mentioned, a technology that in the last years has gained battery market share because of the increased use of EVs. Liu et al., (2021) explain that LIB present high specific energy density and no memory effect (a reduction in the longevity of rechargeable batteries resulting from incomplete discharge in previous uses). The first LIB used in EVs was in Tesla cars in 2008 (Carlier, 2023). According to the study of Liu et al., (2021), in China in 2010, the shares of digital batteries, power batteries, and stationary batteries in LIB in-use stocks were 84.1%, 13.2%, and 2.7%, respectively, in contrast to 10.2%, 74.2%, and 15.6% in 2018. The sharp increase in the share of power batteries can be explained by the extensive use of LIB in EVs.

Moreover, Zhao et al., (2024) affirm that global LIB production is dominated by Asia with China accounting for a 45% share of production, followed by Japan (19%), Europe (15–18%), and Korea (7%).

There are different battery chemistries of LIB, each with different material composition and different characteristics. LIB are a technology that, even though very mature and well-established in the market of EV, is in constant development since companies and manufacturers are working to increase attributes like lifetime, energy density, and battery capacity, so they can deliver a better product to the market (Ding et al., 2019). In this chapter, the structure of these batteries is briefly explained, so it is possible to understand how these battery chemistries differ from each other. In addition, different battery chemistries used in EVs are presented and their differences are emphasized. Lastly, developments and future new technologies are explored to realize the position of LIB in the future of the automotive sector.

2.3.1 Structure of lithium-ion batteries

Li-ion rechargeable batteries are composed of two electrodes, an anode, and a cathode, immersed in an electrolyte and separated by a polymer membrane as represented in Figure 2 taken from (Liu et al., 2016). Also in this picture, the copper (Cu) and Aluminium (Al) current collectors are represented. According to the authors, during the charging process, Li ions are taken out of the cathode and placed into the anode, and during the discharge process, the opposite reaction occurs.

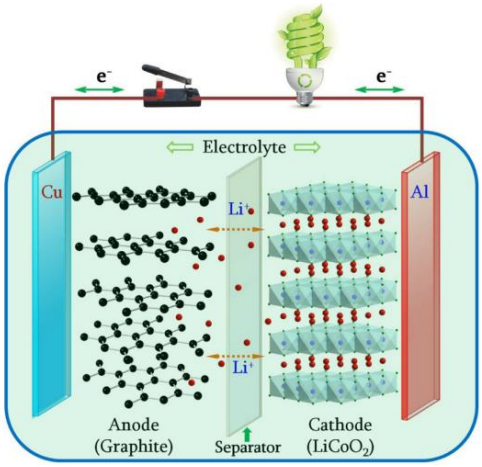


Figure 2: Configuration of rechargeable Lithium-ion batteries (Liu et al., 2016)

The different battery chemistries of LIB differ in cathode composition and as the IEA, (2019) states the three main families of cathode chemistry are lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminium oxide (NCA). In the picture, the cathode mentioned is LiCoO2 which is lithium manganese oxide (LMO), but this battery

chemistry is not considered in this study. Moreover, NMC cathode chemistries have varying ratios of their constituent metals. The IEA, (2020) explains that the NMC 111 battery has equal shares of all three nickel, manganese (Mn), and cobalt materials. Furthermore, NMC 622 is made up of 60% nickel, 20% manganese, and 20% cobalt, and NMC 811 cathode of 80% nickel, 10% manganese and 10% cobalt.

2.3.2 Battery chemistries and their characteristics

Liu et al., (2021) explain that LMO battery chemistry was used in the first EVs, but then was substituted with battery chemistries with higher energy density, and that is why it was not considered in the study. The IEA, (2023) states that NMC111 chemistry was popular until 2015, and after that because of an increase in cobalt price and public concern regarding cobalt mining, a shift towards lower-cobalt ratios, such as NMC622, and then NMC811 started to occur. Nevertheless, the authors also affirm that NMC622 and NMC811 chemistries are more difficult to manufacture. The IEA, (2019) adds that besides NMC chemistries, advanced NCA batteries are expected to be more used, and the IEA, (2022) explains that battery makers are moving to high nickel content chemistries (NMC622, NMC811, and NCA) to achieve higher energy densities and lower costs (cobalt is the most expensive material per kg of LIB). Also, Ding et al., (2019) affirm that during repeated cycling, NMC and NCA chemistries, experience structural and chemical instabilities.

Regarding LFP battery chemistry, Ding et al., (2019) point out that this chemistry possesses more stable crystal structures, and the IEA, (2023) explains that this variant instead of having three or more critical3 materials, it only has one (Li), which reduces concerns about critical materials supplies. xeni & ka, (2022) add that even though this chemistry presents lower specific energy, it offers thermal stability, lowering the risk of fire, and high durability (longer lifetime). The authors resume by saying that LFP batteries are cheaper, safer, simpler to package, and do not require the use of cobalt or nickel (two critical materials). Furthermore, the IEA, (2023) states that LFP batteries are the preferred choice for heavy-duty vehicles (HDV), for presenting high durability and lower cost of production. The authors explain that for commercial operations, high lifetime mileage and affordability are the more important factors. The IEA, (2020) adds that LFP batteries are well suited for HDV due to the wide availability of its materials.

3 (Ren et al., 2023) assess resource criticality and explain that prices and mineral resource scarcity influence the LIB industry. The authors identify Li and Co as highly critical, and Ni and Gr as medium-high critical. Other studies consider also Mn as a critical cathode material.

2.3.3 New technologies and developments

Battery manufacturers work and invest in the improvement of several battery features. As mentioned NMC batteries are shifting toward high nickel content chemistries. Concerning NCA batteries the IEA, (2018) affirms that developments in cell technology are also being made, where higher shares of nickel are being explored compared to the 80% nickel and 15% cobalt of current NCA batteries. Moreover, the IEA, (2022) identifies a recent innovation in LFP chemistries called cell-to-pack (CTP) technology which reduces the weight in the pack and improves energy density to around 85% of an NMC811 battery. These improvements concern the cathode part of the battery, nevertheless the IEA, (2023) points out that even though the focus has been on the cathode, anode improvements are also being made, by doping the graphite anode with silicon, boosting the energy density and charging speeds.

It is clear that battery manufacturers are interested in developments of currently used batteries, but new technologies are also on the horizon of batteries. Kamran et al., (2021) reveal that lithium-metal solid state and lithium-sulphur are being researched, though are not viable for commercialization because of uncertainties in their working capability. The IEA, (2020) adds that after 2030 there will be a number of technologies with the potential to substitute LIB such as the previous two mentioned and sodium-ion and lithium-air technologies. The IEA, (2023) mentions the companies investing in the research and development of lithium-metal solid state and sodium-ion, including auto giants like Volkswagen, BMW, Mercedes, Ford, General Motors, and Hyundai.

Note that, it is not just EVs that are being developed but also other alternative fuel technologies like hydrogen fuel cells and biodiesel. Zhao et al., (2021) explain that today there are some barriers to hydrogen fuel cell technology such as high cost and safety issues but recognizes its potential for future vehicles. Alternative solutions for EV batteries and other fuel technologies could present concurrency to LIB, and constant changes in the EV market could result in a challenge for the recycling industry since these would have to constantly adapt.

2.3.4 Battery recycling

The IEA, (2023) explains that today, LIB recycling is in the beginning stages and that the majority of facilities are located in China. Nevertheless, the authors state that new facilities are being developed in Europe and the United States and that one of the largest recycling facilities is in Germany (which is a neighbouring country of the CZ), a company called Redux which has a recycling capacity of 50kt per year and is able to recycle 95% metal. Moreover, the IEA, (2020) identifies some current LIB recycling facilities all over the world out of which six are in Europe. Two

are located in Finland, one in Sweden, one in Belgium, one in France, and one in Germany (Accurec, different from the one already mentioned). One of the challenges of recycling LIB is the transportation to recycling facilities and logistics which not only involves transportation costs but also CO2 emissions. It is clear that for CZ, ŠKODA, and other European EV manufacturers it is less costly, and less carbon-intensive to recycle these batteries in Europe, and for that, recycling companies, battery manufacturers, governments, and other entities involved need to share knowledge and work together.

Furthermore, since LIB recycling is in an early stage of its development, it can or cannot be economically viable depending on several factors such as recycling costs, recycling methods, and material economic value. Xu et al., (2020) explain in their work the three different recycling methods namely pyrometallurgical, hydrometallurgical, and direct recycling, and study the viability of recycling each LIB material. These will be explored more in detail in Chapter 3 when defining recycling rates.

The IEA, (2020) explains that the processes of pyrometallurgical recycling use high-temperature smelting while hydrometallurgical recycling is based on leaching, removal of impurities, and separation. As for direct recycling, the IEA, (2022) explains that this process allows higher recycling efficiencies since instead of breaking down the cathode into elements, it retains the material crystal structure and regenerates the cathode material. It is a great option for battery cathodes like LFP, which many companies are hesitant to recycle for its little value of materials.

2.3.5 Battery second use

One of the pillars of circular economy is the reuse of products, that are no longer useful in their original application, in other applications where these present a valuable utility. In a linear economy, products are disposed of when they are no longer useful in their initial application, and their potential use in other applications is not assessed. In the case of LIB after finishing their useful life in EVs, these still present 80% of their original capacity and can be used in less energy-demand applications (Zhao et al., 2021). The authors also state that batteries from EVs reused in a second life could contribute to satisfying the increasing demand for electrical energy storage, thus decreasing the need for newly manufactured batteries for this purpose, and explain that while EV LIB represent an opportunity to stationary ESS, LIB from consumer electronics can be reused in other suitable products like solar lights, counterfeit products, toys, and others. In this research, only LIB from EV are considered, so the potential of LIB in ESS is studied. There is some research

regarding the use of these batteries in ESS. Pellow et al., (2020) provide relevant environmental impact insights for decision-making when applying LIB in the grid, and Mcloughlin & Conlon, (2015) study the reuse of batteries from EVs in building integrated photovoltaic applications, for industrial, commercial, and residential applications. Moreover, Peters et al., (2021) explore the opportunities and challenges of grid-scale battery storage.

Reusing LIB is in line with the circular economy and results in a positive impact on the flow of materials since when batteries are reused in a second life, not only their EoL is delayed, but also new batteries that would be produced for these other applications are substituted. However, as Moore et al., (2020) indicate, some factors can limit the potential of LIB for second use such as battery cell failures and technical limits. Xu et al., (2020) add that there is some economic uncertainty due to the costs of repurposing like disassembling, testing, and repackaging, and that battery reuse depends on the chemistry, affirming that for having a longer lifetime, LFPs are more appropriate for second use. Moreover xeni & ka, (2022) add that for having lower prices LFP batteries are more suitable for stationary applications and that these chemistries are expected to dominate the battery storage market. Liu et al., (2021) also affirm that in China mainly LFP batteries are reused in echelon utilization which reduces the pressure of battery recycling for these batteries, and that this application could reduce annually the use of new stationary LFP batteries by 4%.

3 MFA applied to lithium-ion batteries in Czech Republic

A MFA is a valuable tool to quantify materials and study their circularity, particularly in this study of the materials used in Lithium-Ion batteries. BY considering the characteristics of the system, such as the interest in the EV market, recycling capacity, and the variables of a battery's life cycle, like its lifetime, its capacity, and its composition, it is possible to calculate the amount of material that composes batteries entering in EoL, which need careful handling when collected.

Initially in this chapter, the analysed system is defined, including the spatial and time boundaries. The system model is presented as well, allowing to have a good perception of which phase of the battery's lifecycle is studied. Then the goods and materials considered in the study are presented such as the specific battery chemistries and materials analysed, followed by a brief explanation of the resources used and their reliability. Next, the scenarios developed for the MFA are described and finally, all the variables necessary for the MFA are explained in detail.

3.1 System definition

The spatial boundary in this research is the Czech Republic, a country in the very heart of Europe. The time boundary is between 2010 and 2050. Only the EVs sold from 2010 until 2030 are analysed, since after 2030 the battery market is expected to be different compared to the market of today. That is because the technologies used, including LIB, are in constant development, and it is also predicted the rise of new technologies, as explained in the literature review, such as Lithium-Sulphur and Lithium-air batteries (IEA, 2018). For this reason, it is difficult to predict with precision, the future market of batteries, and thus it would not be feasible to include LIB sales after 2030 in the study. Given that the goal of the study is to realize how to manage batteries in End of Life, the years from 2030 until 2050 are also considered, since some of the batteries entering the market from 2010 to 2030 need to be managed in their EoL in the years between 2030 until 2050. The System Model was developed in STAN, and it is presented in Figure 3.

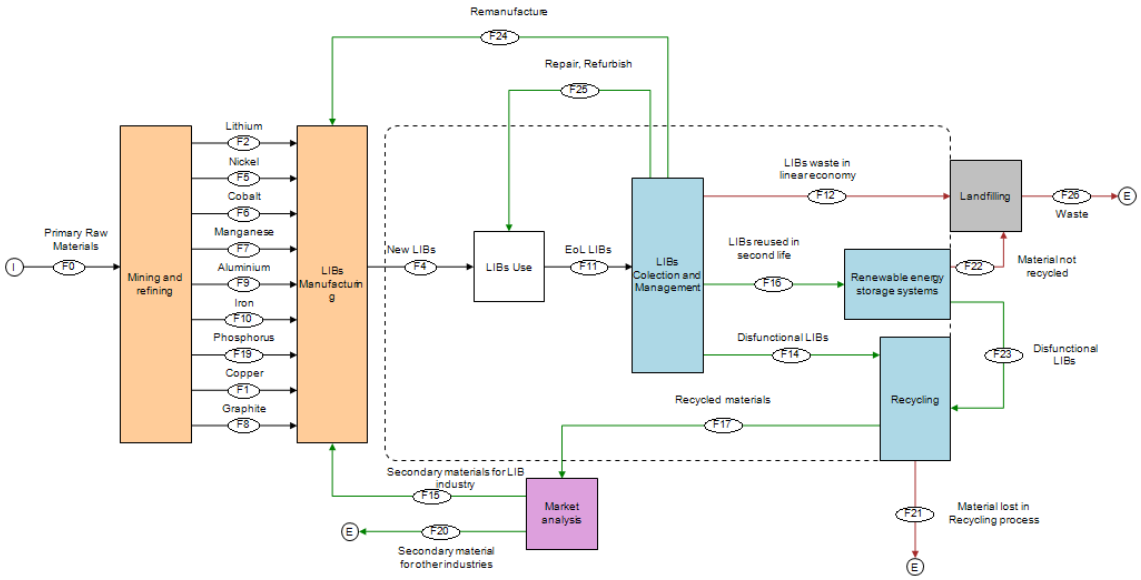


Figure 3: System Model

Flow of material in Circular Economy | Flow of material lost in a linear economy | Flow of material

Production Process | Processes analysed in this research | External Process | Landfilling | First LIB life

The model represents the lifecycle of all materials considered, from the stage of extracting primary raw materials, to disposal or recycling in case the material is recovered. Furthermore, the model represents the connections of all processes and flows of material, and the dotted line delimits the specific processes and flows analysed in this research, from the new LIB entering in the market of EVs to their collection and management in EoL and their destinations. The black arrows represent the flow of materials from the mining of new materials until the EoL of batteries. The dark red arrows represent the flow of material lost in a linear economy plus the waste resulting from the recycling process, and the green arrows the flow of material in a circular economy. Regarding the processes, blue are the main processes studied in this research, crucial for circularity including management, recycling, and reuse of LIB and their materials. In salmon are the processes necessary to create new batteries, and in purple is a market analysis that dictates if the material recycled stays in the LIB industry (closing the loop) or if it goes to another industry. These processes were not analysed in this research. Finally, in grey is the process of landfilling, and in white is the process of use of LIB in EV, both also included in this research.

Regarding the processes analysed in this work, in the collection and management processes, it is decided the path that EoL LIB take, having in consideration the circularity practices in each of the

scenarios developed. In the recycling process, the amount of each material recycled will be calculated, and in the reuse process, the amount of material in kg and the capacity available for a second use will be determined.

3.2 Goods and materials considered

As mentioned before in the research, the MFA is developed for LIB, which have several utilities such as in consumer electronics (mobile phones, laptops, power banks, digital cameras...), in ESS (renewable storage systems or UPS-Uninterruptable power supply), and EV (electric bicycles, cars, buses...) (Liu et al., 2021).

Nevertheless, with the rapid growth of EV sales, it is particularly important to focus on this utility, and the categories of vehicles on which the study will focus, are passenger cars and vans (goods road vehicles with less than 3.5 tons of weight), both categories constituting light-duty vehicles (LDV), and buses and trucks (goods road vehicles with more than 3.5 tons of weight), both categories constituting HDV.

As discussed in the literature review there are several lithium-ion battery chemistries, however, as the IEA, (2022) mentions, today's most relevant cathode chemistry are lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA), and lithium iron phosphate (LFP). In this research, considering a time boundary from 2010 to 2030 regarding EV sales, the battery chemistry studied are LFP, NCA, NMC111, NMC622, and NMC811 for being the most popular in this period. In chapter 2.3.1 of the literature review, it was also explained that LIB consist of an anode and a cathode immersed in an electrolyte and separated by a polymer membrane Liu et al., (2016) and that, what differentiates these technologies is the cathode content. There are other battery components in which Al and Cu stand out for their use in current collectors, cell terminals, thermal conductors, and model and battery enclosures.

In the following Table 4 the materials, of each battery component, that are considered in the MFA are presented. Note that silicon (marked with a *) was not considered in the study, even though, it is a material that has started to be used in anodes, together with the main component graphite (Gr), to increase the energy density of the battery (IEA, 2023). Therefore, only the developments in the cathode composition were considered and not the developments in the anode. Note that in the table, between brackets, it is specified for each material, the battery chemistries in which they are used.

Table 4: Materials considered in the MFA

Cathode	Anode	Electrolyte	Other components (Current collectors, terminals, thermal conductors, module and battery enclosures)
• Lithium (NMC, NCA, LFP) • Nickel (NMC, NCA) • Cobalt (NMC, NCA) • Manganese (NMC) • Aluminium (NCA) • Iron (LFP) • Phosphorus (LFP)	• Graphite • Silicon*	• Lithium	• Copper • Aluminium

Most of the studies regarding lithium-ion batteries focus only on the 4 critical materials used in the cathodes namely Li, Co, Ni, and Mn. In this research, it is also analysed iron (Fe) and Phosphorus (P) since LFP batteries are expected to increase their market share, as explained later in this work. P is a material also used in large quantities in food production, and its increasing use in battery manufacture could result in conflicting demands (IEA, 2023). Moreover, the exploitation of Fe, Cu, and Al metals in a linear economy not only can result in resource scarcity, but also cause air and water pollution, land degradation, and biodiversity loss (EuRIC AISBL, 2020). According to Battery Materials Review, (2024) there was in 2023, a rise in geopolitical risk of Gr. This material is also associated with some environmental impacts. For these reasons, studying these materials' potential circularity in the LIB industry is also relevant.

3.3 Data collection

The data collected and analysed in the research is mostly quantitative and managed alongside the interface Excel. Once the results are obtained these are also applied in the software STAN to create Sankey Diagrams. In this chapter, the sources used to collect the necessary data are named and their reliability is exposed.

3.3.1 Sources

The data in this research was collected from several sources, including previous research on the LIB industry and reports from the Czech government, the European Union, and the International Energy Agency. It was also gathered data from Cista Doprava which is a website created by Centrum Dopravního výzkumu (Transport Research Centre) dedicated to present statistics,

newsletters, reports, articles, and others regarding clean transportation in the country. The Transport Research Centre is a public research institution under the jurisdiction of the Ministry of Transport of the CZ (Transport Research Centre, 2023).

3.3.2 Source confidence and limitation of data

Source confidence

In a research, the data taken from the sources used must be reliable and trustworthy, so that the study does not include incorrect or false information. Reports used from the Czech government and the European Union are naturally accurate and were taken from their official websites. Institutions and Organizations like the International Energy Agency and the World Economic Forum are worldwide recognized for their work and the information taken from these was also from their official websites. Regarding articles and research made by individuals, these were collected from professional networks for scientists and researchers, where academic publications and investigations are shared, allowing researchers to access scientific knowledge and expertise. The most used in this study were Research Gate, Elsevier (Science Direct), and ACS (American Chemical Society).

Limitations

When there is a limitation of data, it is necessary to find ways, logically and rationally, to make calculations, obtain results, and conclude the research by achieving its goal and purpose. If necessary, assumptions can be made in a reasonable way in line with the information available. Many researchers also create scenarios with different variables to compare different possible outcomes, which reduces the uncertainty of results. In this research, both assumptions are made, and scenarios developed, making it possible to consider different future situations and their social, economic, and environmental positive and negative impacts. In the LIB industry, there are some variables that either have low or slightly different information available. This is because lithium batteries are a complex technology, with a lot of characteristics and features to take into consideration. For this reason, it is explained in detail each battery variable considered in the study, such as battery lifetime, battery capacity, material intensity, battery chemistry market share, EV sales, and battery recycling and reuse rates. First, the scenarios are defined and then the variables are presented and explained. The limitations of each data and assumptions are exposed as the variables are presented.

3.4 Scenarios

The scenarios carried out in this research aim to compare the impact of different attitudes and decisions of individuals and economic entities involved in the LIB industry, such as the battery chemistries adopted by battery manufacturers, the improvement of different technologies, development of innovations, efforts towards efficient use of resources and material circularity, consumer role in the energy transition and others. These attitudes and decisions influence the flow of materials in each scenario, like the amount of each material recycled and the amount lost and disposed of. Therefore, three scenarios are developed taking into consideration different values for three of the variables considered. The variables used in the three scenarios are the market shares of different cathode chemistries, the EV sales (specifically between 2025 and 2030), and the recycling and reuse rates of LIB, and each scenario is briefly described next.

Pessimistic Scenario

In the pessimistic scenario, it is assumed that neither individuals nor economic entities have an interest in moving to a sustainable future. Individuals do not embrace the solutions offered for clean mobility and do not show concern for the energy transition and decarbonization in mobility. This is reflected in the variable EV sales, where a low purchase of personal cars is verified. On the other hand, battery manufacturers do not invest in battery chemistries with low content of cobalt, and the progressive adoption of chemistries that are more social and environmentally friendly does not occur. This situation is reflected in the variable battery chemistry market shares. Regarding the recycling and reuse rates variable, these present low values, considering that there is no development in recycling techniques, and the market does not present conditions for recycling factories to prosper. Lastly, governments do not incentivize and create legislation that promotes more responsible decisions regarding all these variables.

Optimistic Scenario

On the contrary, in the optimistic scenario, all entities involved in the transport sector show great concern with achieving a carbon-neutral future, where vehicles do not release GHG to the atmosphere, and the materials used in alternative solutions (in this case EV with LIB) are responsibly managed, and efficiently used in an economy where circularity rules. For this reason, there are high EV sales both for individuals and companies, and the goals stated by the government of the CZ are achieved. The battery market shares mirror a growing interest, over the years, for battery chemistries that present low cobalt content, and the continuing improvement and

innovation of more advanced technologies are present. In this scenario, the conditions offered by the market, including legislation, from the CZ government and the EU, support recycling even to materials that are nowadays not so much recycled in the LIB industry like P and Fe from LFP chemistries, and this is reflected in this study with high recycling rates. Finally, there is a high rate of reuse, of retired batteries from EVs, in other applications like for energy storage of renewable energy sources.

Expected Scenario

In the expected scenario, the values obtained and assumed for market shares, EV sales, and recycling and reuse rates represent the most probable future, where there is some enthusiasm for clean mobility and development. The EV sales continue with the same linear increase trend as the last years, and the market shares of battery chemistries follow the tendency of substituting the use of cobalt, but not as quickly as in the optimistic scenario. With regard to recycling rates, the values assumed express each material's potential for recycling in today's recycling industries, considering also, a reasonable evolution and innovation in this industry. LIB reuse is also considered an opportunity for second-use application of batteries, and LFP chemistries are, as in today's conditions, the cathode chemistry with a more significant reuse rate.

In the next chapter, these scenarios are mentioned when explaining the variables that constitute them.

3.5 Variables and Assumptions

As previously stated, the variables considered are analysed and managed in Excel. The calculations made in this tool are intended to obtain from the number of new vehicles of each category, the quantity of each material that belongs to the EoL batteries. The various steps are outlined in the order they were made:

- From the number of new EVs of each category, the number of new batteries of each chemistry is calculated, by applying the market share of each battery chemistry.
- Then, from the number of new batteries of each chemistry, the number of batteries of each chemistry that reach EoL in each year, is estimated, by considering the battery lifetime.
- Next, the total capacity of each battery chemistry that reaches EoL in each year is calculated by multiplying the number of batteries in EoL by the battery capacity (kWh/battery) of each battery technology.

- Finally, by taking into consideration the material intensity of each battery chemistry, the mass of each material is obtained. Here, with recycling and reuse rates it is also possible to calculate the mass of each material that goes for the different destinations (mass of each material recycled, mass of each material reused in a second life, mass of each material discarded).

These steps summarised the methodology used for the calculations. Each step is explained in detail according to the variables used below. Note that some of these variables are considered in the three scenarios developed, namely pessimistic, expected, and optimistic, and this is also highlighted in the explanation of these variables.

3.5.1 Electric Vehicle Sales

2010-2023

This study includes the sales of electrical vehicles sold in the CZ between 2010 and 2030. Before 2010 the market of these vehicles in the country practically did not exist, and only after 2010, it started to grow with the growing concern for decarbonization. As mentioned earlier in this work, the Ministry of Transport of the CZ exposes statistics regarding transport on a website called Cista Doprava (Clean Mobility), so the new EVs registered in the country from 2010 to 2023, per category of vehicle, were collected, and are shown in the following Table 5.

Table 5: Historical EV sales per year and category of vehicle

	Electric Vehicles			
Year	Passenger cars	Vans	Trucks	Buses
2010	6	0	0	0
2011	56	0	0	0
2012	91	0	0	0
2013	45	0	0	0
2014	217	0	0	0
2015	325	0	0	0
2016	262	0	0	0
2017	387	0	0	0
2018	703	0	0	0
2019	756	33	0	4
2020	3262	44	0	6
2021	2646	172	2	2
2022	3892	134	4	40
2023	6640	353	10	6

As it is observed, until 2018 only passenger cars were sold. New goods road vehicles (commercial vehicles) were registered for the first time in 2019 with 33 vans and in 2021 with 2 trucks. In the case of buses, the first registration was also in 2019. According to the IEA, (2021) the later adoption of electric HDV could be explained by the fact that HDV require large battery capacities, and there were few models available. Now, with developments in battery technology, a greater range of models available, and policies to support companies, electric HDV sales are expected to increase in this decade.

2024-2030

Regarding future EV sales from 2024 to 2030, an estimation of future sales must be done. Two ways to obtain future values from predictions are by using predictions made by someone else (secondary data) and by making its own forecast (primary data). In this work both ways will be used, since for future EV sales, it is intended to consider more than one possibility, thus including this variable in the creation of scenarios. First, research in professional statistical websites was carried out, and in this work, a prediction made by STATISTA, a global data and business intelligence platform established in Germany in 2007, is contemplated. This source has provided information regarding the unit sales of passenger cars from 2024 to 2028 and its last update is from September 2023 (Statista, 2023). For 2029 and 2030 it was applied a linear regression of the five previous years, so the data until 2030 would be completed, and this data is presented in Table 6.

Table 6: Forecast of STATISTA - applied in the pessimistic scenario

FORECAST STATISTA					
Year	Passenger cars	growth rate	Vans	Trucks	Buses
2024	5200	-21,69%	276	8	5
2025	6140	18,08%	326	9	6
2026	7250	18,08%	385	11	7
2027	8560	18,07%	455	13	8
2028	10110	18,11%	537	15	9
2029	11124	10,03%	591	17	10
2030	12348	11,00%	656	19	11

As demonstrated in the table, to find out the future sales of the three other categories of EVs, it was considered the same percentage of annual growth as in the passenger cars category. In 2024 the growth rate was -21,69% since the prediction of STATISTA for this year is 5200 passenger cars,

and the historical sales in the year 2023 for this category of vehicles were 6640, so there is a decrease in car sales. Also, in this forecast, it is predicted little sales compared to the country's goals for these years, as mentioned in chapter 2.2.2. For these reasons, it was assumed that this forecast composes the pessimistic scenario of this work.

There are several methods that can be applied to forecast EV sales. Shafique et al., (2022) made a forecast of LIB sales according to the promotion and incentives plans of the countries analysed, while Dunn et al., (2021) used diffusion models with EV market data and policy targets. Islam & Huda, (2019) used Halt's double exponential smoothing method to predict future sales of EEE (Electric and Electronic Equipment). In this research, it was applied a linear regression using data regarding historical sales from 2019 to 2023. The reason for not using all the historical sales from 2010 until 2023 is that in the first years, there were relatively low sales, and a growing trend was not clear. When applying a linear regression in cases like this, the correlation coefficient R^2 is low as verified in Figure 4.

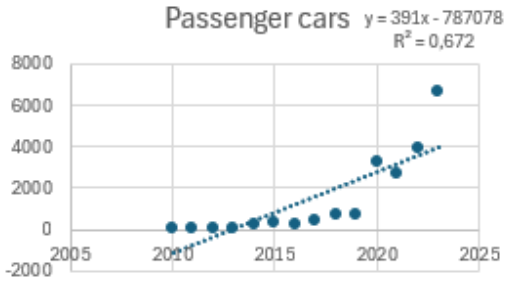


Figure 4: linear regression considering sales from all years 2010-2023 for passenger cars

The correlation coefficient indicates the association between the two quantitative variables (year and cars sold), and the closer it is to 1 the bigger the correlation between the two variables. A coefficient of 0,672 demonstrates that there is some correlation, but as verified in Figure 5, when applying the method of linear regression with only the last five years, the correlation coefficients are higher, and for this reason it is more viable to make future predictions.

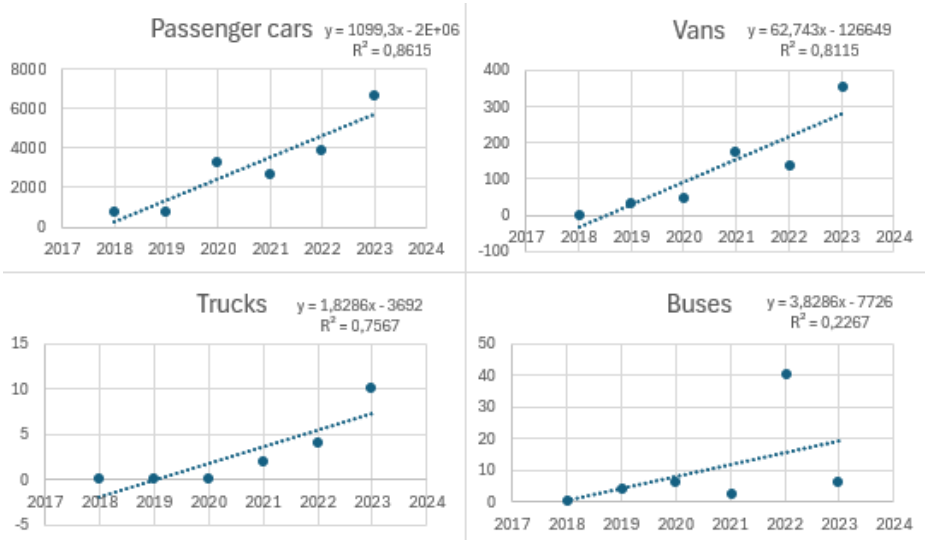


Figure 5: linear regression considering only sales from 2018 to 2023 for all categories of vehicles

The equation and correlation coefficients for each category are presented as well in the previous image, and it is crucial to point out that in the case of the buses category, the coefficient is very low (0.2267) and this is due to the fact that in 2022 the sales of this category were much higher compared to other years. This makes forecasting for this category not so viable, however, as presented in Table 7 these values were still used and assumed to be part of the EV sales in this forecast.

Table 7: Forecast using a linear regression - applied in the expected scenario

FORECAST y=mx+b				
Linear regression using historical data from 2018-2023				
Year	Cars	Vans	Trucks	Buses
2024	7159	366	10	23
2025	8398	439	13	27
2026	9638	512	15	31
2027	10878	585	18	34
2028	12118	658	20	38
2029	13358	731	22	42
2030	14597	804	25	46

This forecast estimates higher future sales for every category compared to the forecast made by STATISTA. By 2030 the predicted sales of cars, vans, trucks, and buses are 18%, 22%, 33%, and 410% higher respectively. For this reason, this forecast is included in the Expected Scenario.

For last, the EV sales considered in the Optimistic Scenario are based on the targets set by the CZ, and already identified in this research, where, by the end of 2030, the annual EV sales reach

44000 units (Ministry of Industry and Trade, 2015). To create a scenario that would move towards this goal, the sales of each of the four categories of electric vehicles were considered to have an annual increase of 30%. The results are shown in the following Table 8.

Table 8: Forecast considering the CZ targets for EV sales - applied in the optimistic scenario

Forecast considering CZ targets					
Year	growth rate	Cars	Vans	Trucks	Buses
2024	30%	8632	459	13	8
2025	30%	11222	597	17	10
2026	30%	14588	776	22	13
2027	30%	18965	1008	29	17
2028	30%	24654	1311	37	22
2029	30%	32050	1704	48	29
2030	30%	41665	2215	63	38

The sum of EVs predicted to be sold in 2030, from all four categories, is 43981 units, which practically achieves the goal defined by the government of the CZ. Nevertheless, having into consideration that the total number of all types of vehicles sold annually is around 214654 on average (according to the statistics of Cista Doprava regarding the last five-year sales of all types of vehicles), this estimated future sales of 43981 EVs would represent 20,5% of all total sales. This is still a small value of EV share when compared to the EV30@30 Campaign that 14 countries embraced, aspiring to reach 30% of EV share by 2030 (IEA, 2021).

Limitations

The main limitation in the variable EV sales is the fact that in the expected scenario a linear regression to the category of buses was used even though there was a weak correlation between year and historical sales (R^2= 0,2267), caused by much higher sales (40 buses) in 2022 of these vehicles compared to other years. Because of this, the future sales of this category were predicted to be even higher compared to the sales of buses in the optimistic scenario. Nevertheless, the sales in 2022 could mean that there is an interest in investing in these vehicles, so the values calculated were used in the study.

3.5.2 Battery Chemistry Market Share

Once the sales of all EVs were obtained it was necessary to understand which battery chemistry each of these vehicles used, have been using, and will use in the future. The study of this variable was very sophisticated since there are various chemistries of LIB in the market each one with

different material composition, characteristics, advantages, and disadvantages. In chapter 2.3 of the literature review, these details were explained, and as mentioned in chapter 3.2 the LIB chemistries considered in the work were NMC 111, NMC 622[4], NMC 811, LFP, and NCA. The market dominance changed over the years and predicting the future most popular chemistry is also complicated, since these technologies are in constant development, and their market supply depends on several factors from social and political, to economic and environmental. Also, it is complicated to find detailed information regarding the exact market shares of each chemistry, especially for past years, in which, in much research and reports, just vague information is presented. Most studies focus on future perspectives, and these have slightly different data. For these reasons, the battery chemistry market shares over the years are also integrated into the three different scenarios developed.

Initially, it was gathered in Excel useful information regarding all five different battery chemistry market shares, from several reports of the International Energy Agency, regarding EV and critical minerals, to considerations and assumptions made by some LIB articles. To complete this data, it was gathered information provided by an analyst of Benchmark Mineral Intelligence, an organization specialized in assessing market prices, supply chain data, forecasting, and strategic advisory for lithium-ion batteries, and other technologies crucial to the energy transition (Benchmark Mineral Intelligence, n.d.). The historical market shares were defined, which are the same in all scenarios, and the future market shares were assumed in each scenario, by combining information from several sources. The market shares of battery chemistries are naturally different for LDV and HDV since these present different needs.

Light-duty Vehicles

With respect to light-duty vehicles, the market shares for the expected scenario are presented in Table 9, and in blue the future market shares of this specific scenario are represented. This scenario was the first to be defined as these shares represent the more likely future use of battery chemistries, considering the tendencies of today's market.

Table 9: LDV market shares in the expected scenario

	NMC111	NMC622	NMC811	NCA	LFP
2010-2014	35%	0%	0%	11%	1%
2015-2019	33%	24%	1%	31%	0%

[4] There are other mid-nickel NMC chemistries such as NMC532 and NMC721 but in this work it was assumed that all mid-nickel NMC chemistries are 622.

2020-2024	7%	34%	17%	6%	31%
2025-2030	1%	19%	33%	3%	41%

The values from the first ten years (from 2010 until 2019) are based on the article made by (Dunn et al., 2021). In this research, the market shares of four different regions, China, Europe, the US, and Row (rest of the world) are provided. It is verified that there are some differences between these regions, where China stands out for the extended use of LFP and, for an anticipated start in the development of more advanced technologies like NMC622 and NMC811. Nevertheless, as CZ belongs to Europe the values used were from this region. This source shows a considerable use of LMO technology in the region in the first five years (2010-2014), however, in this study, this technology was not considered because during this period the EV sales were not significant. After this period these batteries lost market share and are not predicted to be used in the future, so they are not relevant in this study. That is why, from 2010 to 2014 the chemistries analysed in this study represent only 47% of the total market share. As for the period between 2015 to 2019 it is seen a significant increase in the use of NMC622 and NCA, and the battery chemistries analysed in this work represent 89% of the total market share. The first NMC811 batteries entered in the market because of the effort from battery producers to create a battery with higher energy density and lower cobalt content.

For the period between 2020 to 2030 the data was collected from an analysis of (Benchmark Mineral Intelligence, 2024). In this analysis, it was specified the market share of several chemistries in the years 2020, 2025, and 2030, as shown in Appendix A. For 2025 and 2030 this organization made a forecast and since it is a professional entity specialized in the LIB industry, it is considered to be a reliable source to indicate an accurate future prevision. Most of the reports from this source require a purchase, and this specific data was acquired by contacting the organization and receiving feedback from one analyst. So, for the study, it was assumed that the market shares for the period of 2020-2024 would be the average between 2020 and 2025 and that for the period of 2025-2030 would be the average between 2025 and 2030. For being a trustworthy source, the values for the period 2025-2030 were the values used in the expected scenario, as mentioned above. Note that after 2020, when the sales of EVs are much higher and significant, the chemistries analysed in this work in the periods 2020-2024 and 2025-2030, represent 95% and 97% of all EV market share respectively.

Concerning the pessimistic and optimistic scenarios the market shares from 2010 to 2024 are the same as in the Expected scenario since these represent historical values. So, only in the period between 2025 and 2030, the market shares change. In the following Table 10. the values used in the Pessimistic scenario are presented.

Table 10: LDV market shares in the pessimistic scenario

	NMC111	NMC622	NMC811	NCA	LFP
2010-2014	35%	0%	0%	11%	1%
2015-2019	31%	24%	1%	31%	0%
2020-2024	7%	34%	17%	6%	31%
2025-2030	7%	55%	20%	0%	15%

The values from 2025 to 2030 were assumed considering that little development would be made from 2025 on, and so, NMC622 chemistries would continue to dominate the market. With little development, LFP batteries would not increase their energy density with improvements in their technology, and for this reason, would lose market share. Furthermore, it is assumed that in a pessimistic future, little concern is paid to the reduction of cobalt content in batteries, which not only is toxic for the environment but also represents social and economic problems as explained in the literature review. This is another reason why, in this scenario was considered a lower market share of LFP chemistries (which does not contain Co), and a small increase in NMC811 share, which from NMC batteries, is the one with the lowest Co content.

On the other hand, the optimistic scenario shown in Table 11, considers that today's trend to reduce the use of Co rules also in the future and that efforts to improve LFP energy density continue. Also due to LFP's greater suitability for second use, a market with LFP batteries could result in greater reuse rates of LIB.

Table 11: LDV market shares in the optimistic scenario

	NMC111	NMC622	NMC811	NCA	LFP
2010-2014	35%	0%	0%	11%	1%
2015-2019	31%	24%	1%	31%	0%
2020-2024	7%	34%	17%	6%	31%
2025-2030	0%	7%	40%	0%	50%

In this scenario, supported by a continuous development of batteries, NMC811 chemistry also gains market position, since it is the one with lower Co content, compared to the ones that also have this material in their composition. In an optimistic scenario, it was assumed that a balanced use of different materials, in line with circularity, should prevail, and that is why LFP and NMC811 compete in this scenario for market dominance.

Heavy-duty Vehicles

With respect to HDV, it was not considered a change in the chemistry preference over the years. The first HDV registered in the country was in 2019, and from that moment until 2030 it is considered that in each scenario, the market shares of battery chemistries used, were always the same. This assumption was made due to the fact that it was not possible to find specific information that identified a change over the years for these specific categories of vehicles.

The IEA, (2020) defined in its study, scenarios for the cathode chemistry of HDV namely "low cobalt case", "high cobalt case" and a "central value" which is the average between the two cases. These seemed appropriate to integrate into the scenarios of this work, so the high cobalt case is integrated into the pessimistic scenario, the low cobalt case in the optimistic scenario, and the expected scenario considered the average of the previous two. These values are presented in Table 12, and as it is shown, it is assumed that HDV only use NMC622 and LFP chemistries.

Table 12: HDV chemistry market shares 2019-2030

	NMC111	NMC622	NMC811	NCA	LFP
Pessimistic scenario	0%	20,0%	0%	0%	80,0%
Expected scenario	0%	12,5%	0%	0%	87,5%
Optimistic scenario	0%	5,0%	0%	0%	95,0%

Limitations

There are some limitations related to this variable, that influence in the accuracy of this study and they are identified as:

- For LDV, the market shares from 2010 to 2019, collected from the article mentioned, are from Europe, and from 2020 to 2030 the data collected, from Benchmark, is regarding all world. This study is focused only on the CZ.
- Lack of detailed data, and sometimes slightly different data from source to source. This is because the market of LIB is complex and in constant change.

- In LDV, from 2010 to 2014 the chemistries analysed compose only 47% of the market in that period.

3.5.3 Battery lifetime

The battery lifetime is one of the characteristics that battery producers work hard to improve since the short lifetime of batteries is one of the reasons, that makes some buyers sceptical about this technology, which results in buyers choosing other vehicles rather than electrical ones. Ziemann et al., (2018) argue that the useful lifetime of batteries is expressed as the loss of the battery's ability to provide a specific amount of its original nominal capacity, usually 80%. Hu et al., (2024) explain that this percentage is denominated as the state of health (SOH) and that batteries in EOL with a SOH superior to 85% are directly used in less energy-demanding vehicles, that batteries with a SOH between 80% and 85% are reused in ESS and that bellow 80% they go to recycling (battery cascade utilization). According to Xu et al., (2020) the lifetime of batteries in the real world depends on several factors, like rates of charge and discharge, driving cycle, and ambient temperature. Shafique et al., (2022) also add that road conditions, maintenance, materials used, battery capacity, and degradation rate influence the lifespan of batteries, and affirms that with the use of innovative materials, technologies, and battery performance management this lifespan is expected to grow in future years.

All these factors can be considered to estimate the battery lifetime nevertheless, in this work, it is only relevant to estimate the average lifetime of batteries in the number of years. Knowing the new number of batteries in the market in each year, and their lifetime in years it is possible to realize in which year the batteries reach their EoL. Therefore, it is assumed that once finishing their useful life in years, in an electric vehicle, LIB reach 80% of their original capacity. At this point, batteries are collected and managed, and it is decided if these are either taken to recycling or used in a second life according to recycling and reuse rates respectively (defined and explained later in this work). The batteries that do not follow either of these two paths are assumed to be disposed of.

Many studies assume battery lifetime taking into consideration the warranty of the several brands of cars, and some authors like Hu et al., (2024) assume that the battery lifetime (8 years) is shorter than the average vehicle lifetime (15 years), while Ziemann et al., (2018) and Kamran et al., (2021) consider a higher battery lifetime of 10 years. Because of the uncertainties and the several factors that influence this variable Shafique et al., (2022) used a Weibull distribution to stimulate variance in the battery lifespan and considered this variable in his scenarios assuming that the lifetime varies

from 4 to 20 years. Xu et al., (2020) explain that LFP chemistries have a longer lifetime and that these can reach 20 years having a medium lifespan of 15 years.

Taking into consideration all these sources, plus some of the reports of the IEA regarding the EV outlook like the IEA, (2020), it was defined the battery lifetime for this work for all five chemistries analysed. It was also considered that over the years there are improvements in the technology and materials used, so it is assumed a linear increase of this feature. The battery lifetime (in years) assumed for all battery chemistries analysed is shown in Table 13.

Table 13: Battery lifetime (years)

Year	NMC 111	NMC 622	NMC 811	NCA	LFP
2010-2019	8	8	8	8	14
2020-2024	10	10	10	10	16
2025-2029	12	12	12	12	18
2030	14	14	14	14	20

With the following information, it is possible to verify the following assumptions:

- In the first ten years there was no improvement in this variable, and only from 2020 there is a linear increase every 5 years, assuming that the interest in improving this feature appeared only in the second half of the previous decade, with the growing interest for EV.
- NMC and NCA chemistries' lifetime is assumed to be the same over the years and LFP's lifetime is higher for the reasons already mentioned.
- The battery lifetime is assumed to be the same as the EV lifetime. So, when a battery reaches its EoL it is not considered its replacement by a new one in the same car.
- Battery lifetime is considered to vary only with the chemistry and the years, but it is not related to the vehicle category.

Limitations

The main limitations of the values used for this variable are, as stated above, the fact that it was not used a distribution that would include variance in the data and that this is a variable that, because it depends on several technological factors and consumer behaviour in the utilization of the product, is difficult to define.

3.5.4 Battery capacity

The next variable to be addressed in this work is the battery capacity. Once the amount of each battery chemistry entering EoL for every year is obtained, it is needed to convert the information from the number of batteries of each chemistry to the total capacity of each chemistry entering EoL. From this point, it is possible to calculate the mass of each material that is not used in second life (also considering the material intensity explained in the following chapter), and the total capacity available for second use.

Battery capacity refers to the capacity that batteries have, to generate energy in a period of time, and it is measured in kWh (amount of energy in kW that can be generated in one hour). The greater the battery capacity, the greater the driving range of EVs, and that is why this feature has also been a focus of improvement and development in the automotive industry in the last years. As the IEA, (2019) explains, the battery capacity in electric cars has increased from 20-30 kWh in 2012 to 35-70 kWh in 2018, and this trend will continue until most electrical cars have battery capacities of 70-80 kWh, which means a driving range of more and less 350-400 km. The authors of this IEA report also alert to the fact that an increase in battery capacities will result in an increased demand for new materials. Shafique et al., (2022) study the battery capacity in China and USA and affirm that the average battery capacity in China in 2015, 2020, 2025, and 2030 is 42kWh, 57kWh, 64kWh, and 75kWh respectively, and that in the USA for the same years is 44kWh, 61kWh, 73kWh, 86kWh respectively. Ziemann et al., (2018) confirm the trend for the increase of battery capacity towards 85kWh from the initial 20-25kWh. Some authors consider only the average battery capacity by the time they wrote their articles and others assume a linear increase.

One solution to improve the battery capacity is to produce bigger and heavier batteries, however the IEA, (2022) highlights that battery makers have been moving over recent years, to higher nickel content chemistries to achieve higher energy density thus improving the battery capacity. This trend is both in NMC and NCA chemistries as these are composed with nickel in their cathode. Not only developments in the cathode improve the energy density, but also in the anode with the integration of silicon with graphite. It is important to bear in mind that it is not just the materials used that improve this variable, but also other innovations like cell-to-pack that aim to remove some components, reducing weight and thus improving energy density (IEA, 2020).

Since this study analyses LIB that enter the market and are produced between 2010 and 2030, it is considered a linear increase in battery capacity over the years. Not only it is considered a linear

increase, but it is also assumed different battery capacities for the several chemistries analysed in this work. Having taken into consideration all the sources mentioned regarding the improvement, over the years, of this variable in LIB and the influence that the materials and technologies used have on it, it was defined the following battery capacities for LDV presented in Table 14. Even though, in the real world, the vehicle category vans have slightly bigger batteries with slightly higher battery capacities compared to passenger cars, it is assumed that these are values for all LDV including both passenger cars and vans.

Table 14: LDV Battery capacity of each chemistry (kWh)

	NMC 111	NMC 622	NMC 811	NCA	LFP
2010-2014	25	-	-	25	25
2015-2019	30	35	55	40	35
2020-2024	35	50	65	55	45
2025-2029	40	65	75	70	55
2030	45	80	85	85	65

As verified, there is a linear increase in all chemistries for the reasons explained, and some batteries have, for the same period, higher battery capacity than others, since, some cathode chemistries have higher energy density than others. For example, LFP batteries have lower energy density as part of their nature compared to others. It is assumed that NMC 111 cathode chemistry, for being a technology losing market share over the years, has little improvement in its capacity. Another detail of this data is that it is not assumed any battery capacity for NMC 622 and NMC 811 for the first period (2010-2014), for not being in the market at that time.

On the other hand, the difference between LDV and HDV battery sizes and battery capacities is very considerable, so the battery capacity for HDV must be considered apart from the previous information. For both buses and trucks, the following Table 15 was defined, where the battery capacities are presented, in the several years, for each category and the average between them.

Table 15: HDV battery capacity (kWh)

HDV battery capacity (kWh)			
	Trucks	Buses	Average of HDV
2010-2014	any sales	any sales	any sales
2015-2019	any sales	215	215
2020-2024	110-300	215	208,333
2025-2029	130-325	230	228,333
2030	150-350	250	250

To calculate the capacities for the period of 2020-2024, data provided by the IEA, (2023) was used, where four different categories of buses and two categories of trucks, from 2019 to 2022 years, were considered. The two values, for each period, in the trucks' column represent the medium and heavy trucks. For the year of 2030, the predicted future values for these categories by the IEA, (2020) were assumed. Lastly, for the 2025-2029 period, the intermediate value between the two previously explained periods was assumed. Reminding that the first sales of HDV in the CZ was in 2019 for the category of buses, so for the period 2015-2019 it was assumed the same value of buses as in the 2020-2024 period.

The values used in the calculations of this work are the ones in the column *Average of HDV*, and these were obtained by calculating the average of the three values of each line, representing the average battery capacity of HDV for each period.

Limitations

The battery capacity varies in all 4 categories, nevertheless, for the sake of simplicity, it was defined values only for LDV and HDV. The goal of the work is to find solutions for batteries at the end of life, and it would be too complex if it would be calculated the amount of each material for each category. For this reason, by not considering the information for each category, the data is not as accurate as it could be.

3.5.5 Material intensity/metal content

To calculate the amount of each material analysed, it is necessary to know the proportions used in each of the five LIB technologies considered in this research. In the LIB industry, the material content in batteries is stated as the amount of material in kg needed for 1 kWh of capacity (kg/kWh). For this reason, by multiplying the material intensity in kg/kWh, of one specific material, for the capacity of one battery in kWh, it is obtained the amount in kg of that material in one battery. By following the same reasoning, by multiplying the material intensity in kg/kWh, of one specific material, for the total capacity, regarding all batteries of a specific chemistry in EoL, it is obtained the total mass in kg of that material, that composes all batteries of that specific chemistry in EoL.

After considering in the calculations all the variables previously explained such as EV sales, battery chemistry market share, battery lifetime, and battery capacity, the total capacity of each battery chemistry reaching EoL is known. From this point, it is only needed the material intensity of each

material in the different battery chemistries, so it is possible to calculate the mass of each of the materials considered such as Li, Ni, Co, Mn, Al, Fe, P, Gr, and Cu.

After gathering the data from several sources, it was concluded that many sources studied the material intensity of Li, Ni, Co, and Mn for the different chemistries. This is due to the fact that most researchers focus only on these critical materials that compose the battery's cathode. Less attention is given to Al, Fe, P, Gr, and Cu nevertheless, these are also crucial to have in consideration when studying the circularity of battery materials as explained in Chapter 3.2. Therefore, for Li, Ni, Co, and Mn five different sources were contemplated, namely Li & Xu, (2022), Kamran et al., (2021), IEA, (2018), IEA, (2023), and Dunn et al., (2021). The mean and standard error were calculated for each material, which allows to consider possible variability in the data from this point on, in the work. Cencic & Rechberger, (2008) also apply the standard error in their work where a MFA is developed with the software STAN as well. The authors explain that the standard error is more suitable than the standard deviation for the software STAN. Moreover, as explained in Chapter 1.1 this software uses mathematical statistical tools, like error propagation and gross error detection, to verify the accuracy and validation of the data. The values obtained for the 4 critical materials mentioned are presented in Table 16.

Table 16: Material intensity of key materials in battery chemistries (kg/kWh)

	Average Li	Standard Error Li (±)	Average Ni	Standard Error Ni (±)	Average Co	Standard Error Co (±)	Average Mn	Standard Error Mn (±)
NCA	0,1038	0,003119	0,7065	0,022381	0,13525	0,004029	0	0
NMC111	0,1418	0,002955	0,37825	0,010136	0,379	0,009983	0,3515	0,008846
NMC622	0,1226	0,002315	0,5886	0,019356	0,1946	0,006063	0,1868	0,006437
NMC811	0,1086	0,002182	0,699	0,032879	0,0868	0,003967	0,0832	0,00372
LFP	0,0970	0,00178	0	0	0	0	0	0

On the other hand, for the rest of the materials (Al, Fe, P, Gr, and Cu) only one source was used for each, so the standard error was not applied. The material intensity of these materials is shown in Table 17 and the sources used were IEA, (2023) for Fe and P, and Dunn et al., (2021) for Al, Cu, and Gr.

Table 17: Material intensity of other key materials in battery chemistries (kg/kWh)

	Al	Fe	P	Cu	Gr
NCA	2,92	0	0	0,564	0,978
NMC111	3,11	0	0	0,677	0,978
NMC622	3,017	0	0	0,605	0,96

NMC811	2,921	0	0	0,549	0,961
LFP	3,528	0,72	0,39	0,946	1,085

Limitations

The main limitation of the data used for this variable is the fact that for Al, Fe, P, Cu, and Gr only one source was used, so the accuracy of this data depends only on the accuracy of the sources used. There are very few studies regarding these materials, and even though they might not be as critical as the first four mentioned it is also important to consider them. As explained before in the work Gr is also a critical material and others like P could in the future present some challenges in their supply.

3.5.6 Recycling and Reuse rates

Once the quantities of each material that compose batteries in EoL are calculated, the recycling and reuse potential is assessed. Regarding reuse rates, by considering them for each battery chemistry, the total capacity available for a second use is calculated. Concerning recycling rates, of each material studied, these allow the calculation of the amount of secondary material, available for the manufacture of new batteries (closing the loop), or other products in other industries. Note that, in this research, only the batteries that were not taken into a second life, were considered for the possibility of recycling, with some being recycled and others not, according to the rates assumed. It was not analysed the management of batteries after being used in a second application. Naturally, after using these batteries in a second life, the same reasoning should be taken, by understanding if these could be still used for some purpose, and if not, what would be their recycling potential.

In this work, it is assumed that the collection rate is 100% and that in recycling processes 5% of material is lost. Nevertheless, defining recycling and reuse rates for each material is complex and so, in order to determine which values represent better reality, several sources were examined, and recycling scenarios were defined, as it was done with other variables in this study. Hu et al., (2024) consider two scenarios for recycling rates, with the more conservative being 85% for Li and 98% for Co, Ni, and Mn, and the more positive scenario, all four materials reaching 99% recycling rates by 2060. Dunn et al., (2021) assume a recycling rate of 95% for all four critical materials (Li, Ni, Co, and Mn). Ziemann et al., (2018) affirm that lithium recycling processes do not imply high recovery efficiency, so the authors defined 40% and 80% recycling rates in their scenarios for this material. Moreover, Shafique et al., (2022) develop three different recycling scenarios, where he

also assumes lower recycling rates for Li such as 50%, 75%, and 90%, compared to Co, Ni, and Cu where the authors define for the three scenarios, recycling rates of 85%, 90%, and 95%. Xu et al., (2020) explain as shown in Figure 6, the three different recycling methods and the viability of recycling each of these materials in each recycling method.

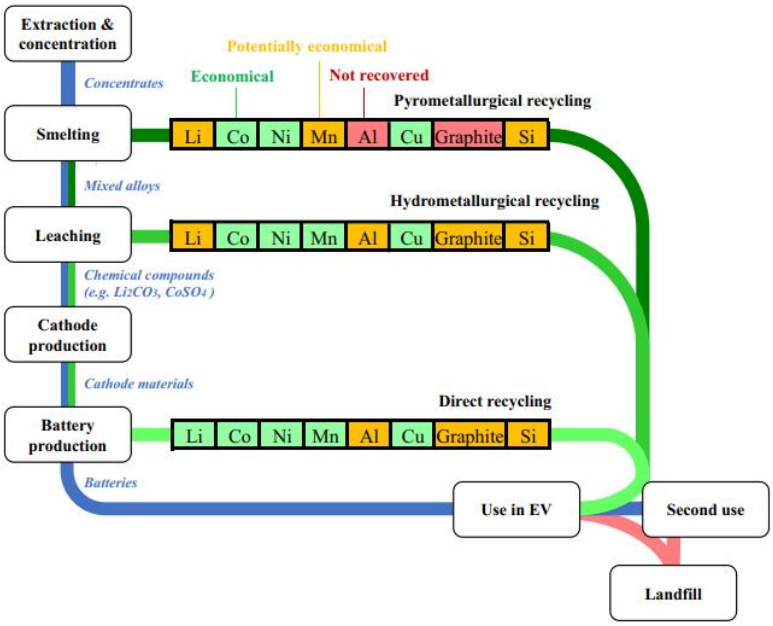


Figure 6: LIB materials and their recycling potential in different recycling methods

In their work he explains that Li in both Pyrometallurgical and Hydrometallurgical methods can or cannot be economically viable depending on its price and recycling scale, however, it is viable to recycle in the Direct Method. The authors also clarify that in Pyrometallurgical Gr is burnt off and Al is not economically viable, so it is not considered by recycling companies specialized in this process, and that in Hydrometallurgical the viability is also uncertain for these two materials. Lastly, these authors reveal that Co, Ni, Mn, and Cu are materials with great potential for recycling.

Furthermore, Braunfels & Teuber, (2023) present the targets for recovered materials set by the EU Battery Regulation, where it is stated that no later than 31 December 2031 a minimum level of 95% recovered Co, Ni, and Cu, and 80% recovered Li should be achieved. In this regulation, it is also set the goal of achieving, by 31 December 2030, 70% recycling efficiencies of lithium-based batteries.

Regarding Fe and P Or et al., (2020) clarify that little work has been done with LFP batteries since Fe is an abundant, low cost and environmentally benign material. P is also low-cost and not a critical material, so the recycling of LFP batteries is not economically viable. Nevertheless, it is

possible to recycle these batteries. Li et al., (2017) use common reagents and a simple process to recover Li, Fe, and P from these batteries, and Zhao et al., (2024) enumerate nine other studies, each with different methods for recycling, but all with leaching efficiencies above 90% for Li and Fe and some also for P. For these reasons, these materials were also considered to have a good potential for recycling at a scientific level. On an economic level, it is considered in this study, that the materials can or cannot be viable depending on the efforts and commitment of all entities involved in its recovery.

Therefore, taking into account the information analysed, recycling rates were defined for the three scenarios and are presented in the following Table 18.

Table 18: Material recycling rate (%) in the different scenarios

	Pessimistic scenario	Expected scenario	Optimistic scenario
Li recycling rate	40%	70%	95%
Ni recycling rate	80%	90%	100%
Co recycling rate	80%	90%	100%
Mn recycling rate	80%	90%	100%
Al recycling rate	30%	60%	95%
Fe recycling rate	0%	90%	100%
P recycling rate	0%	90%	100%
Cu recycling rate	80%	90%	100%
Gr recycling rate	30%	60%	95%

As observed, for Ni, Co, Mn, and Cu the recycling rates were assumed to be the same and relatively high because of the recycling potential that these have. With respect to Al and Gr, as it was explained, there are some barriers to the recycling of these materials, so the recycling rates were assumed to be lower. Even though Li presents also some challenges in the recycling process, for being a critical metal with a higher interest in the LIB industry the recycling rates were defined to be higher compared to Al and Gr in the pessimistic and expected scenarios. Finally, in the pessimistic scenario, it was considered that Fe and P were not recovered, assuming that there is no interest in LFP recycling due to the low value of these two materials. However, because of an increasing trend in the sales of these batteries, and because there are several possibilities to recycle them, it is assumed that in the Expected and Optimistic scenario, these two materials have recycling rates of 90% and 100% respectively.

Concerning the second life, as explained in Chapter 2.3.5, LFP batteries are the most fitting technology mainly for their long lifespan. Even though there is some research that considers the same recycling rates for all batteries like Shafique et al., (2022), who defined for their three scenarios reuse rates of 0%, 25%, and 50%, there are others that distinguish the second-use application rates for LFP, NMC, and NCA batteries. Xu et al., (2020) assume a 100% reuse rate for LFP, and a 50% reuse rate for NMC and NCA batteries before 2020 and 75% after 2020. The authors also consider a second life of ten years. Bearing in mind the information exposed, reuse rates are defined for this work and are presented in Table 19. Note that in this work the battery lifetime in the second use is assumed to be 10 years.

Table 19: Battery reuse rates (%) in the different scenarios

	Pessimistic	Expected	Optimistic
LFP	50%	80%	100%
NMC	0%	50%	75%
NCA	0%	50%	75%

Limitations

The recycling rates are assumed to be the same for all years evaluated in this study, so it is not considered the evolution of recycling techniques over the years. Naturally, it is expected that in the first years, the recycling opportunities would not be as wide as in the later years. The same happens with reuse rates since this work does not consider the increasing interest over the years for a second use of LIB. The same recycling and reuse rates in all years may not indicate accurate results for some specific periods. Moreover, today's recycling rates in real life may not be as high as the values presented in this work. The values assumed for this research are having in count the potential for recycling of each material and also recycling rates assumed in other research. So, in general, in all scenarios, the recycling rates are relatively positive compared to reality, and a lot of work has to be done to increase recycling rates in the real world.

4 Results and discussion

In the following chapter various results are presented, mainly from the calculations made with the variables presented earlier. With these it was possible to obtain the demand for each material over the years, the amount of material that constitutes batteries reaching EoL, and the quantity of material reused and recycled. The materials that constitute EoL LIB need to be well managed, and the existing solutions allow these either to prolong their use, or to recover them and apply them in new battery production, and that is why the quantification of material in the several stages of the battery life cycle is essential. For example, by knowing the amount of a specific material recycled, in one particular year, it is possible to realize its contribution in satisfying demand for the same year. The amount of material disposed of and not recovered is also calculated and the comparison between scenarios is made.

Not only the material was quantified in different stages of the battery lifecycle, but also the amount of battery capacity available for second use was calculated, which allows us to understand its contribution to the storage of energy produced by RES for the grid in the CZ. Moreover, in this chapter, it is discussed the economic impact of each scenario regarding the material recycled and the material disposed of.

4.1 Lithium-ion battery materials flow and their impact

In this chapter, the quantities of each material in the several stages of the LIB lifecycle, like initial demand, material entering EoL, material recycled, material reused, and material disposed are presented.

4.1.1 Material demand

Regarding the demand for each material, there has been an increase over the years in all scenarios as all scenarios consider a growing purchase of EVs over the years. Nevertheless, the demand is much higher in the optimistic Scenario compared to the other two, since in this scenario the targets for EV sales by 2030 are achieved. In this scenario, the demand for Li, Ni, Co, Mn, Al, Fe, P, Cu, and Gr will increase respectively to 190.126 t, 678.523 t, 101.395 t, 97.227 t, 5.835132 kt, 596.142 t, 322.910 t, 1.336309 kt, and 1.852466 kt in 2030, compared to 17.734 t, 69.424 t, 18.665 t, 16.397 t, 500.401 t, 34.060 t, 18.449 t, 110.484 t, and 159.039 t in 2020. On the other hand, In the expected scenario, the demand for Li, Ni, Co, Mn, Al, Fe, P, Cu, and Gr will increase respectively to 122.258 t, 471.439 t, 91.423 t, 82.523 t, 3.613662 kt, 306.645 t, 166.100 t, 809.885 t, and 1.149310 kt in 2030, compared to 17.736 t, 69.479 t, 18.684 t, 16.414 t, 500.353 t, 33.993 t, 18.413 t, 110.452 t, and 159.027 t in 2020. Lastly, in the

pessimistic scenario, the demand for Li, Ni, Co, Mn, Al, Fe, P, Cu, and Gr will increase respectively to 113.032 t, 507.704 t, 146.356 t, 139.959 t, 2.972496 kt, 95.611 t, 51.789 t, 621.812 t, and 947.345 t in 2030, compared to 17.739 t, 69.535 t, 18.702 t, 16.432 t, 500.305 t, 33.925 t, 18.376 t, 110.420 t, and 159.016 t in 2020. The materials demand in each scenario for every year from 2018 to 2030 is presented in Appendix B, including the standard error for the four critical materials Li, Ni, Co, and Mn, which indicates the possible deviation in the amount of material calculated.

A significant increase in materials demand starts in 2020 and the following Figure 7, Figure 8, and Figure 9 show respectively the increase for the pessimistic, expected, and optimistic scenarios for all materials.

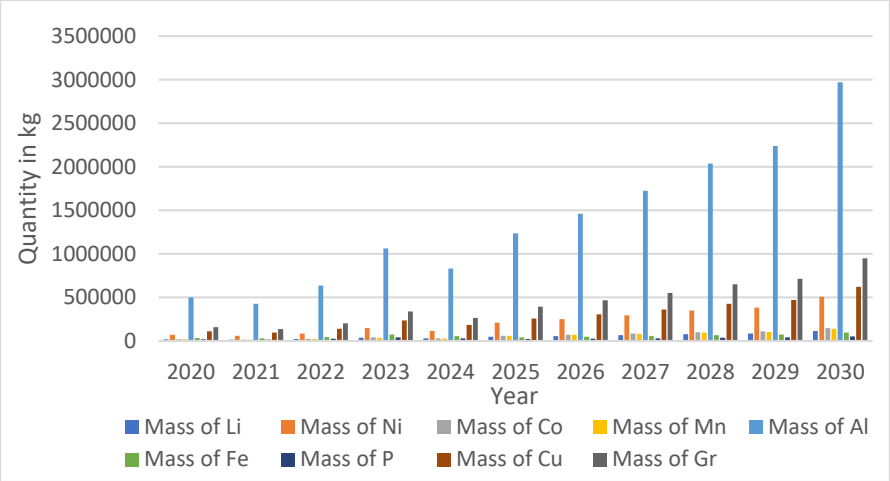


Figure 7: Material demand in the pessimistic scenario

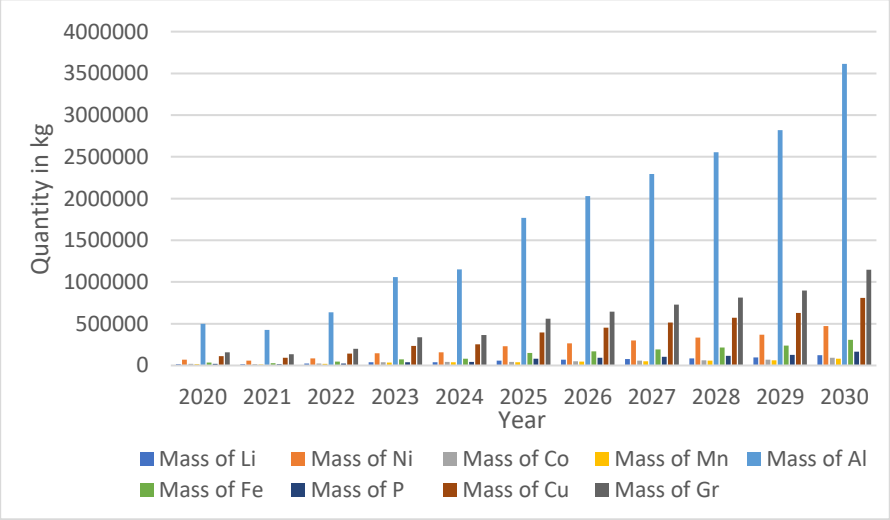


Figure 8: Material demand in the expected scenario

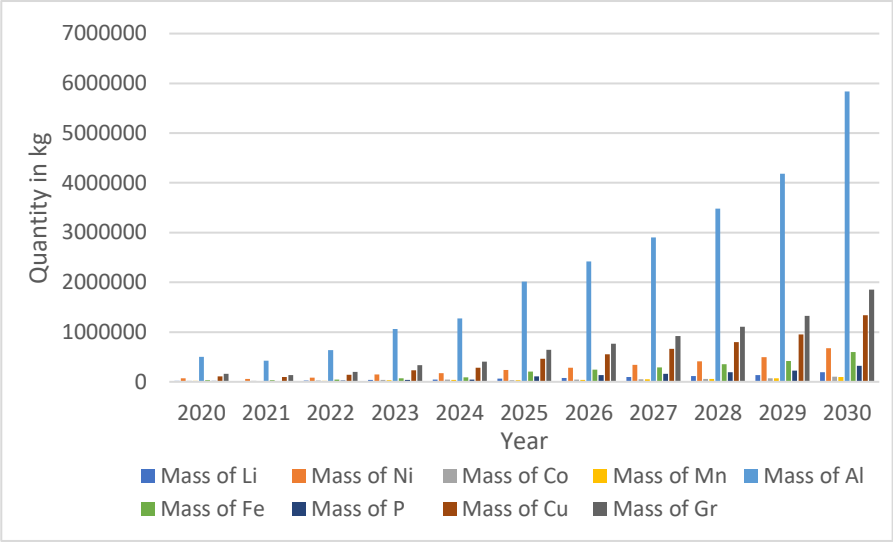


Figure 9: Material demand in the optimistic scenario

4.1.2 Material in EoL batteries

Concerning the amount of material that constitutes EoL batteries, the amounts calculated for each year from 2018 to 2050 are presented in Appendix C for the three scenarios. This work involves batteries that entered the market in 2010 and that the shorter lifetime assumed is eight years for NCA and NMC technologies, and that is why the first batteries reaching their EoL appear for the first time in 2018. Naturally, the amount of material that constitutes EOL LIB is greater in the optimistic scenario than in the expected and pessimistic scenarios, as the amount of material demand, due to the higher amount of EVs sold in the optimistic scenario.

In this work, in the periods 2028-2029, 2035-2036, and 2042-2043 few batteries are reaching EoL, and this is due to the fact that a 2-year increase in battery lifetime every five years was assumed, considering the development of batteries lifespan over the years as explain in chapter 3.5.3. The batteries that reach EoL in these periods are LFP since they have different battery lifetimes. Note that, for this reason, from the point where it is estimated when batteries reach EoL forward, there is not a perfect increasing tendency over the years in the scenarios, in the quantity of material that is either recycled, taken to second use, or disposed of, even if over the years the increasing tendency for new EV and consequently demand material, is easily verified and close to linear. Nevertheless, there is still an increase in the amount of material that goes for second use, recycling, and disposal, but with significant drops in the three periods referred. This is observed in Figure 10, regarding the expected scenario, where the material reaching EoL has an increase over

the years, but with drops in the periods previously explained. The same tendency happens similarly with pessimistic and optimistic scenarios.

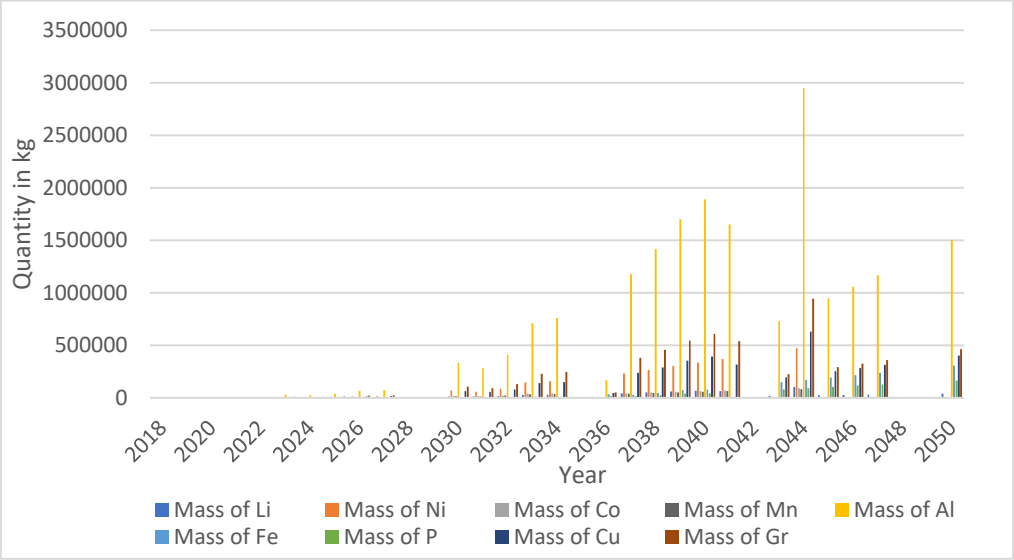


Figure 10: Quantity of material in EoL LIB - expected scenario

The last NCA and NMC batteries considered in the study reach their EoL in 2044, and after that year only in 2050, the last LFP batteries considered reach EoL. In all scenarios, the amount of Li, Ni, Co, Mn, Al, Cu, and Gr entering EoL, reaches their peak in 2044, while for Fe and P, the higher amount entering EoL is in 2050. This justifies the fact that after 2044 the material entering EoL, even though also with an increasing tendency, is lower since it only concerns LFP batteries.

Regarding the four critical materials that compose the cathode part of the battery, in the pessimistic scenario in 2044, it is estimated that 106570 kg of Li, 507704 kg of Ni, 146356 kg of Co, and 139959 kg of Mn reach EoL, while for the same year in the expected scenario 104036 kg of Li, 471439 kg of Ni, 91423 kg of Co, and 82523 kg of Mn reach EoL. As for the optimistic scenario 142628 kg of Li, 678523 kg of Ni, 101395 kg of Co, and 97227 kg of Mn reach EoL in 2044. Moreover, the total amount of Li needed to be managed from 2018 to 2050 in the pessimistic, expected, and optimistic scenarios is 575637 kg, 653766 kg, and 827707 kg respectively. The total amount of Ni for the three scenarios is estimated at 2515569 kg, 2543281 kg, and 3034438 kg. As for Co, the total amount in these scenarios is 718557 kg, 537510 kg, and 526589 kg, and for Mn 672708 kg, 478839 kg, and 488900 kg. The total amount of Li and Ni stands out in the optimistic scenario where the number of batteries is higher and there has been a commitment to using battery cathodes with a high content of nickel with the NMC811 chemistry. For both Co and Mn, these present higher values in the pessimistic scenario since in this scenario there is no effort

in using low cobalt chemistries which may result in an unsecured and unstable supply chain, where environmental problems, derived from Co toxicity, and sociopolitical issues are faced. Mn presents higher quantities in this scenario since NMC622 is the cathode that leads the market, instead of the lower Mn content NM811 chemistry, that thrives alongside LFP in the other two scenarios.

On the other hand, the quantity of cathode materials used in LFP chemistries in EoL, such as Fe and P, present their higher value in 2050, which corresponds to the EV sold in 2030 with a battery expected lifetime of 20 years, since in 2030 these batteries achieve in two scenarios the highest sales of all years for this technology, and because the battery capacity (which also influences the material content) is the highest in 2030. Thus in 2050, the quantity of Fe entering EoL in the pessimistic, expected, and optimistic scenarios is respectively 95611 kg, 306645 kg, and 596142 kg, and the accumulated from 2018 to 2050 is 617157 kg, 1536571 kg, and 2376493 kg. As for P, the amount entering EoL in 2050 is for pessimistic, expected, and optimistic scenarios respectively 51789 kg, 166100 kg, and 322910 kg, and the accumulated from 2018 to 2050 is 334294 kg, 832309 kg, and 1287267 kg. Note that P in the optimistic scenario presents higher quantities and, in this case, an evaluation of the utilization of this material in LIB compared to its demand in the food industry is pertinent so it is understood the possible demand conflict between the two markets for this material.

Lastly, the three components analysed that do not make up the cathode, namely Gr in the anode, and Al and Cu in other battery components, represent the higher values of material reaching EoL since these have a higher proportion in battery composition. The amount of these materials entering EoL reaches its peak in 2044, whereas for Al it is predicted an amount in the pessimistic, expected, and optimistic scenarios respectively of 2737496 kg, 2950911 kg, and 4107576 kg. For Cu 558799 kg, 632174 kg, and 873081 kg, and for Gr 875074 kg, 945488 kg, and 1321174 kg. Moreover, the accumulated amount of material that reaches EoL for all the time considered in the study (2018-2050) is in the pessimistic, expected, and optimistic scenarios respectively 15374267 kg, 19106477 kg, and 24983772 kg for Al, 3256176 kg, 4262841 kg, and 5675305 kg for Cu, and 4898518 kg, 6078360 kg, and 7937015 kg for Gr. Of these three, Gr is the most critical material, so it is crucial to manage it well, and as explained in chapter 3.5.6, it presents some obstacles in the recycling process. Even though in the optimistic scenario there is a 95% recycling rate for this material, in a real situation where there would be the same number of sales as in the optimistic scenario, the recycling process would need a significant improvement so the material could be recovered and follow a circular economy.

4.1.3 Material used in a second life

Next, the amount of material that constitutes batteries reused in a second life is presented. Even though batteries finish their useful life in EVs, it is possible to reuse them in other applications, as already mentioned in this work, prolonging their lifetime. In this research, the optimistic scenario is the one that takes more batteries for a second life since in this scenario it is assumed that 100% LFP, 75% NMC, and 75% NCA batteries are used in a second application.

In the following Figure 11, it is compared between scenarios the total amount of material that is used in a second life for all the years studied (2018-2050). It is possible to verify that Ni, Co, and Mn do not present any material in the pessimistic scenario and that is because NMC and NCA are not utilized in second life in this scenario. Moreover, it is not possible to observe in the graph the amount of Li in the pessimistic scenario since it is a small quantity, 41572 kg, compared to Al, Fe, P, Cu, and Gr with 1512036 kg, 308579 kg, 167147 kg, 405438 kg, and 465011 kg respectively in the same scenario. However, in the optimistic scenario, there is a much more considerable amount of all materials used for a second life with 700822 kg of Li, 2275828 kg of Ni, 394942 kg of Co, 366675 kg of Mn, 21649033 kg of Al, 2376493 kg of Fe, 1287267 kg of P, 5037091 kg of Cu, and 6848072 kg of Gr. Regarding the expected scenario, where half of NMC and NCA batteries and 80% of LFP batteries that reach EoL are reused, there is a more realistic but considerable amount of material reused with 653766 kg of Li, 2543281 kg of Ni, 537510 kg of Co, 478839 kg of Mn, 19106477kg of Al, 1536571 kg of Fe, 832309 kg of P, 4262841 kg of Cu, and 6078360 kg of Gr.

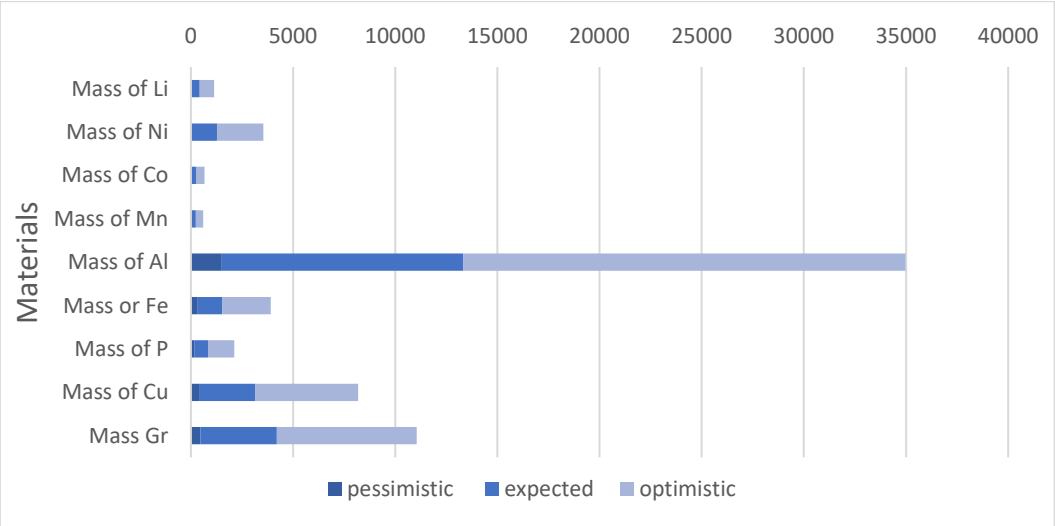


Figure 11: Quantity of material used in second life (tonnes) in the three scenarios

4.1.4 Capacity used in second life

EOL LIB repurposed for a second life is more relevantly studied when it is considered the capacity available for this purpose, so then it can be compared with the electricity produced by renewable energy sources in the country and understand in which proportion can batteries contribute to the storage of clean energy. In the literature review, it is explained that EV LIB have been subject to research for second use in ESS, and this research explores their potential in the electricity grid of RES since these also play an important role in today's energy transition. Therefore, the battery capacity available for second use in each scenario was compared with the electricity produced by photovoltaic, hydro, and wind energies in the CZ.

Regarding the available battery capacity in each scenario, it is assumed that once batteries start their second life, they last for 10 years in the grid. Thus, for each year the capacity available for a second use is totalized with the sum of a given year's capacity with the previous 9 accumulated. Note that the annual battery capacity that goes for a second life was obtained as explained in chapter 3.5.4. From that capacity, only 80% is considered, assuming that after being used in EV, batteries retain only 80% of their initial nominal capacity. Moreover, even though HDV have bigger batteries and with higher capacities compared to LDV, their capacity is studied together, for two reasons. First, because both are appropriate for ESS, as mentioned in the literature review, and second because the total annual capacity available for second use from HDV is low since the sales of these vehicles are low in the country. So, it would not be interesting to study these categories separately.

Regarding the electricity produced by renewable energies first, the historical electricity production from 2018 to 2023 was identified for the three renewable energies considered (Electricity Maps, 2024). Then, the electricity production from 2024 to 2030 was estimated considering the same annual growth as the expected installed capacity in the country from 2024 to 2030 for the three energies considered, indicated in the NECP of the Czech Republic Government, (2019) and presented in Appendix D. Finally, for the remaining period, the expected electricity production from 2031 to 2050 was estimated with a linear regression using the previous 7 years (from 2024 to 2030), so the same increasing tendency would be followed.

Figure 12 demonstrates the impact that each scenario would have if these batteries were integrated into the hydro, wind, and solar ESS of the CZ.

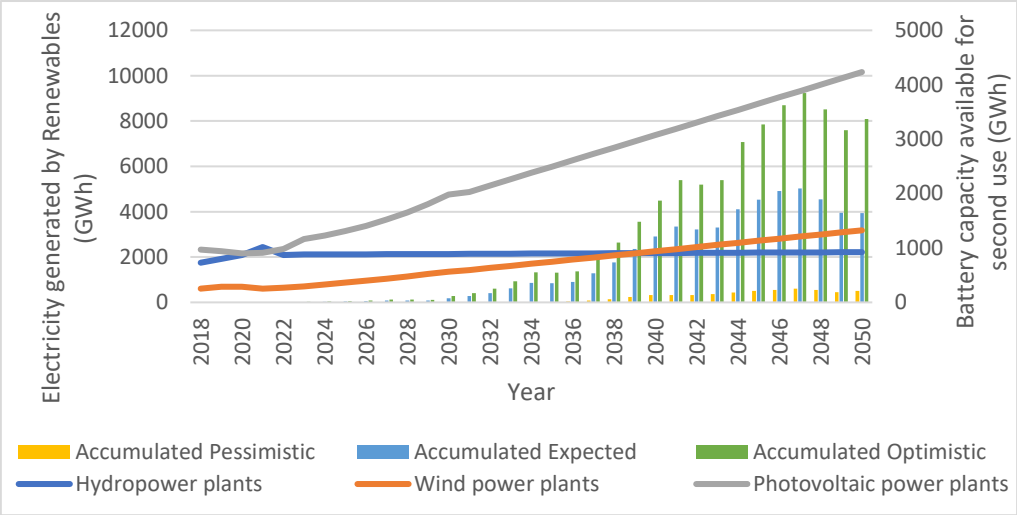


Figure 12: Comparison between battery capacity available for second use from EoL LIB and Electricity generated by renewable energies in the CZ

Only after 2030, a considerable contribution from batteries to the storage of energy is obtained, and after 2044, LIB could make a significant contribution to the management of the grid and smooth the effect of variable renewable energy sources such as wind and solar power. The results show that the capacity of these batteries could reach a value close to the expected wind and hydropower generation in the expected scenario, which demonstrates the high potential of LIB for second use. As for the optimistic scenario, it would even surpass the annual electricity production by wind in all years from 2044 to 2050, and by hydro in all years from 2041 to 2050 except in 2042. In 2047, in all scenarios, the maximum contribution from batteries to the storage of energy is achieved with 254.6 GWh, 2093.1 GWh, and 3849 GWh in pessimistic, expected, and optimistic scenarios respectively, representing for each scenario 1.76%, 14.51%, 26.68% of the total amount of energy expected to be produced in 2047 by the three renewable energies considered. Note that in the years 2048 and 2049, a decrease in the capacity available for second use is expected, since in these years there are no batteries reaching EoL in EVs. Also in these years, the batteries that started to be used in the grid in the years 2038 and 2039, reach their useful life in the grid in the years 2048 and 2049 respectively (10 years after the start of their use in the grid). For these reasons, there are fewer batteries available for the grid, so the capacity available for storing energy in the grid is lower. In the pessimistic scenario, the availability for second use comes later since only LFP batteries are considered for second purposes, and these have longer lifetimes. Even so, the contribution in this scenario is insignificant in all years, which means that almost all batteries used in the grid would have to be newly manufactured ones, increasing the intensity of production and the need for mining and exploration of other resources.

As explained in the literature review one of the challenges of reusing LIB is the fact that it must undergo several processes that are costly and time-intensive. Dismantling, testing, reconfiguration, and repacking are all necessary processes to adapt the battery to its new application. Nevertheless, reusing batteries presents a great solution for the circularity of materials and a more sustainable LIB industry as verified in the optimistic scenario.

4.1.5 Material recycled

With regard to the amount of material recycled, the amount of each material recycled in each year from 2018 to 2050, for each scenario, was calculated and is presented in Appendix E. Note that first, in the MFA applied in this study, from the amount of material that reached EoL in EVs it is calculated the amount of material that is reused. Then, from the material that was not repurposed in a second life (in this case in the grid for the storage of energy produced by RES), it is calculated the amount that is either recycled or disposed of.

Moreover, to have a broader perspective of the period considered, the total amount recycled from 2018 to 2050 was calculated. Moreover, the data was inserted in the software STAN, and as explained in Chapter 1.1, it is not possible to insert in the program and analyse more than one period (insert data regarding each year), so the sum of the total amount of each material recycled from 2018-2050 was applied in the software. As stated in chapter 3.5.6 a material loss of 5% was assumed in the process of recycling so the amount lost in recycling is also calculated, not for each year, but only for the total amount from 2018 to 2050. Finally, the economic value of all recycled material was calculated, by multiplying the amount of each material by its respective price. The price of Li, Ni, Co, Mn, Al, Fe, and Cu was collected from Trading Economics, an entity that provides information to 196 countries with 20 million economic indicators, exchange rates, commodity prices, and others (Trading Economics, 2024). As for the price of P it was acquired from Index Mundi and Gr from BusinessAnalytiq. The price of each material in USD per tonne is presented in Appendix F.

These results are presented in Table 20, Table 21, and Table 22 which correspond to the pessimistic, expected, and optimistic scenarios respectively.

Table 20: Total amount recycled, lost in recycling, and economic value from 2018-2050 - pessimistic

	Mass of Li	Mass of Ni	Mass of Co	Mass of Mn	Mass of Al	Mass of Fe	Mass of P	Mass of Cu	Mass of Gr
Total amount recycled (kg)	202944	1911833	546103	511258	3950736	0	0	2166560	1263549

Total amount lost in recycling (kg)	10681	100623	28742	26908	207933	0	0	114029	66503
Economic value of material recycled (USD)	2955276	39293894	14826706	2873271	10817115	0	0	23264527	1415175

Table 21: Total amount recycled, lost in recycling, and economic value from 2018-2050 - expected

	Mass of Li	**Mass of Ni**	**Mass of Co**	**Mass of Mn**	**Mass of Al**	**Mass of Fe**	**Mass of P**	**Mass of Cu**	**Mass of Gr**
Total amount recycled (kg)	176079	1087253	229785	204704	4157853	262754	142325	1304521	1336377
Total amount lost in recycling (kg)	9267	57224	12094	10774	218834	13829	7491	68659	70336
Economic value of material recycled (USD)	2564059	22346307	6238673	1150436	11384202	31005	21776	14007944	1496743

Table 22: Total amount recycled, lost in recycling, and economic value from 2018-2050 - optimistic

	Mass of Li	**Mass of Ni**	**Mass of Co**	**Mass of Mn**	**Mass of Al**	**Mass of Fe**	**Mass of P**	**Mass of Cu**	**Mass Gr**
Total amount recycled (kg)	114514	720679	125065	116114	3009602	0	0	606304	982771
Total amount lost in recycling (kg)	6027	37930	6582	6111	158400	0	0	31911	51725
Economic value of material recycled (USD)	1667551	14812116	3395512	652559	8240291	0	0	6510489	1100704

The materials Li, Ni, Co, Mn, Al, Cu, and Gr are recycled in a higher quantity in the pessimistic scenario, compared to the optimistic, resulting for this reason also in a higher economic value of recycled material. This is due to the fact that in the optimistic scenario, there are many more batteries being reused in the grid after their useful life in EVs. So, even though the proportion of material recycled within all the material not reused is lower in the pessimistic scenario, due to low recycling rates, there is still a higher quantity of material recycled compared to the optimistic scenario. It is logical that once reused LIB in the optimistic scenario are no longer useful in the grid, these would be recycled in much bigger proportions in the future. As stated earlier, in this scenario, a more significant contribution of LIB in the grid starts in 2030, and considering that LIB are used in the grid for ten years, it is expected that only around 2040 there will be a more significant amount of materials recycled in the optimistic scenario. Note that, this would mean that even though the optimistic scenario is the one closest to circular concepts, it is a scenario where the material demand until 2040 would depend mostly on mining to satisfy the increasing demand for EVs until 2040.

In a case like this, would it be better to recycle some batteries directly even when they are appropriate for a second use? On the other hand, it would probably result in a higher demand for new batteries to the grid. In this research, this dilemma is presented as the realization that what seems to be a sustainable solution can create also some difficulties, so it is important to always look at the bigger picture to understand what are the most sustainable solutions.

Regarding Fe and P in the pessimistic scenario, there is no amount of material recycled because it is considered that there is no interest in recycling LFP batteries, due to their little value materials. In the optimistic scenario, both these materials are also not recycled since LFP batteries are all considered for reuse, and the evaluation of the material destination after the second life is not assessed in the work.

Furthermore, the amount of material recycled in each year (between 2018 and 2030) is compared with the material demand in the respective year, in order to determine in which proportions secondary material would satisfy the annual demand for materials. The results for scenarios pessimistic, expected, and optimistic are expressed in the following Figure 13, Figure 14, and Figure 15 respectively.

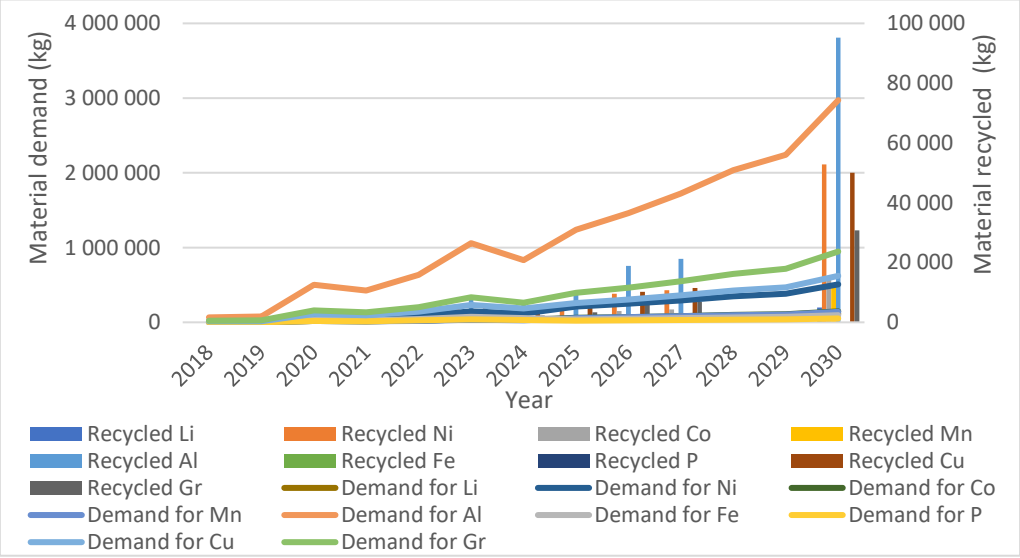


Figure 13: Comparison between recycled material and demanded material - pessimistic

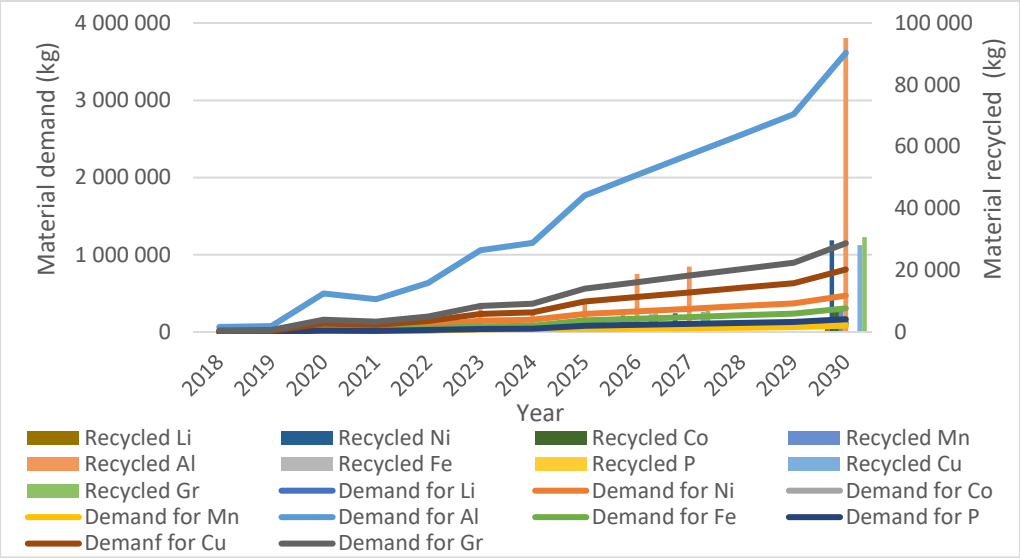


Figure 14: Comparison between recycled material and demanded material - expected

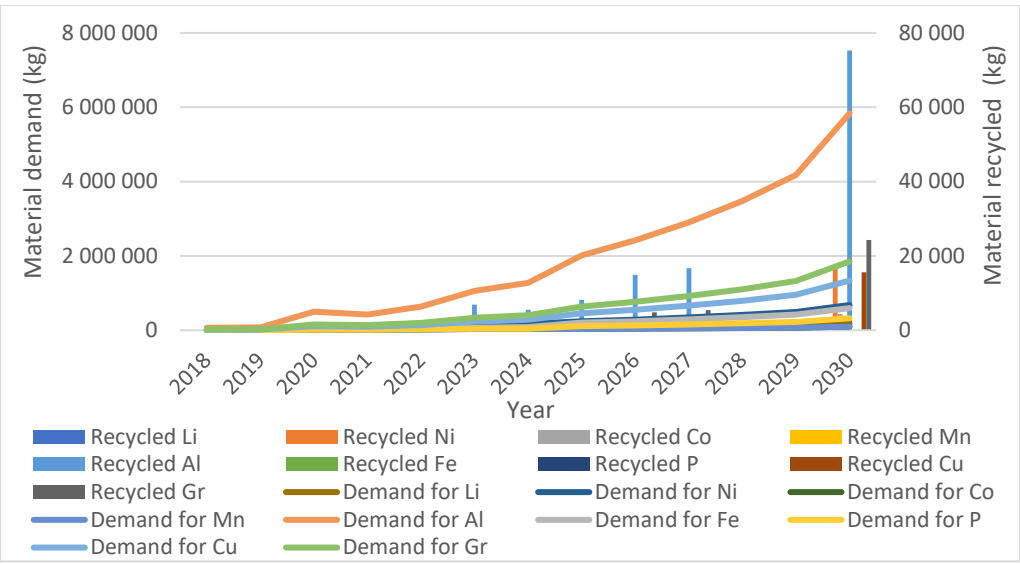


Figure 15: Comparison between recycled material and demanded material - optimistic

As it is observed in the figures the highest material demand and quantity of material recycled in all scenarios occur in the year 2030. As EV sales are only considered until 2030 no further material calculations are presented after this year. So, for being the year with more significant values, the percentage of material demand satisfied with recycled material is assessed and the values are presented in the following Table 23 for all three scenarios.

Table 23: % of material satisfied with recycled material in 2030

		Mass of Li	Mass of Ni	Mass of Co	Mass of Mn	Mass of Al	Mass of Fe	Mass of P	Mass of Cu	Mass Gr
Pessimistic scenario	Material recycled in 2030 (kg)	5004	52846	14213	12488	95210	0	0	21895	22776
	CMUR in 2030 (%)	4,43%	10,41%	9,71%	8,92%	3,20%	0,00%	0,00%	3,52%	2,40%

Expected scenario	Material recycled in 2030 (kg)	4375	29702	7987	7017	95129	0	0	28125	30724
	CMUR in 2030 (%)	3,58%	6,30%	8,74%	8,50%	2,63%	0,00%	0,00%	3,47%	2,67%
Optimistic scenario	Material recycled in 2030 (kg)	2966	16488	4433	3894	75247	0	0	15611	24302
	CMUR in 2030 (%)	1,56%	2,43%	4,37%	4,01%	1,29%	0,00%	0,00%	1,17%	1,31%

As verified the amount of material recycled in 2030 is higher in the pessimistic scenario for most of the materials for the same reason as explained before (little reuse of batteries in this scenario), and this is also reflected in the (CMUR) circular material use rate. This rate represents the % of material demanded satisfied with recycled material. In the optimistic scenario even though 4,37% of Co and 4,01% Mn of material demand is satisfied with secondary material, there is still a considerable amount that needs to be mined, being that the total demand for these materials in this year is 101,395 kg Co of and 97,227 kg of Mn.

4.1.6 Material disposed

In all scenarios, there is a certain quantity of material that is lost and disposed of right after LIB reach their EoL in EVs. This represents the material that is neither recycled, nor reused, considered waste of a linear economy where products are produced used, and disposed of. In this research, it was calculated the total amount from 2018 to 2050 and their economic value was assessed, and the values are shown in Table 24.

Table 24: Total material disposed of from 2018-2050 in the three scenarios

		Mass of Li	Mass of Ni	Mass of Co	Mass of Mn	Mass of Al	Mass of Fe	Mass of P	Mass of Cu	Mass Gr
Pessimistic scenario	quantity disposed of (kg)	320438	503114	143711	134542	9703562	308579	167147	570147	3103455
	Economic value (USD)	4666225	10340499	3901765	756124	26568353	36412	25573	6122244	3475869
Expected scenario	quantity disposed of (kg)	79434	127164	26875	23942	2917792	30731	16646	152576	937809
	Economic value (USD)	1156718	2613603	729669	134554	7988914	3626	2547	1638356	1050346
Optimistic scenario	quantity disposed of (kg)	6344	0	0	0	166737	0	0	0	54447
	Economic value (USD)	92384	0	0	0	456526	0	0	0	60981

As verified the materials with a higher potential for recycling such as Ni, Co, Mn, Fe, P, and Cu are not directly disposed of in the optimistic scenario and the only waste from these materials comes from the recycling process where 5% of material is lost as already mentioned and presented in Chapter 4.1.5 (quantity of material recycled). As for Li, Al, and Gr, despite not being fully recycled in the optimistic scenario, they present small quantities of disposed material compared to the expected and pessimistic scenario, even though in the optimistic scenario the materials present higher quantities reaching EoL because of the higher use of these vehicles. In the pessimistic scenario, there is a higher quantity of material recycled because few batteries are reused and almost all material is either recycled or disposed of as already discussed. It is noted that even though the material recycled was the highest in the pessimistic scenario, the proportion of material recovered is smaller, meaning that in this scenario the quantity of material disposed of is much higher. Critical materials like Li, Ni, Co, and Mn reached a total quantity of material disposed of 320.4 t, 503.1 t, 143.7 t, and 134.5t respectively with an economic value of 4,666,225 USD, 10,340,499 USD, 3,901,765 USD, and 756,124 USD. Note that Al is the material with a higher amount of material lost with 9703.6 t with a value of 26,568,353 USD in the pessimistic scenario.

The material disposed of not only represents an economic waste but also a threat to the health of ecosystems since some of these materials can create environmental damage when not properly managed and disposed of. In future research, it would be interesting to calculate the costs involved in recycling these materials and compare them to their economic value to understand how profitable it would be to recycle them.

4.2 Sankey diagrams

To complement the MFA, the quantity of material reused, material recycled, material lost in the recycling process, and material disposed of are inserted in STAN obtaining the Sankey diagrams where it is possible to recognize the different flow of materials between the several processes after the collecting and management process of LIB in EoL. These quantities inserted in the software correspond to the total flow of materials between 2018 and 2050, the period of the investigation that presents batteries in EoL. The diagrams also expose the standard error for Li, Ni, Co, and Mn materials which allows us to identify the possible deviation of results according to different values used in the variables, in this case in the material intensity as previously explained. In the following Figure 16, Figure 17, and Figure 18 the Sankey diagrams of all three scenarios, pessimistic, expected, and optimistic respectively are presented. The colours of the several processes and flows

differentiate them according to the purpose of this research, and they were explained in detail in Chapter 3.1.

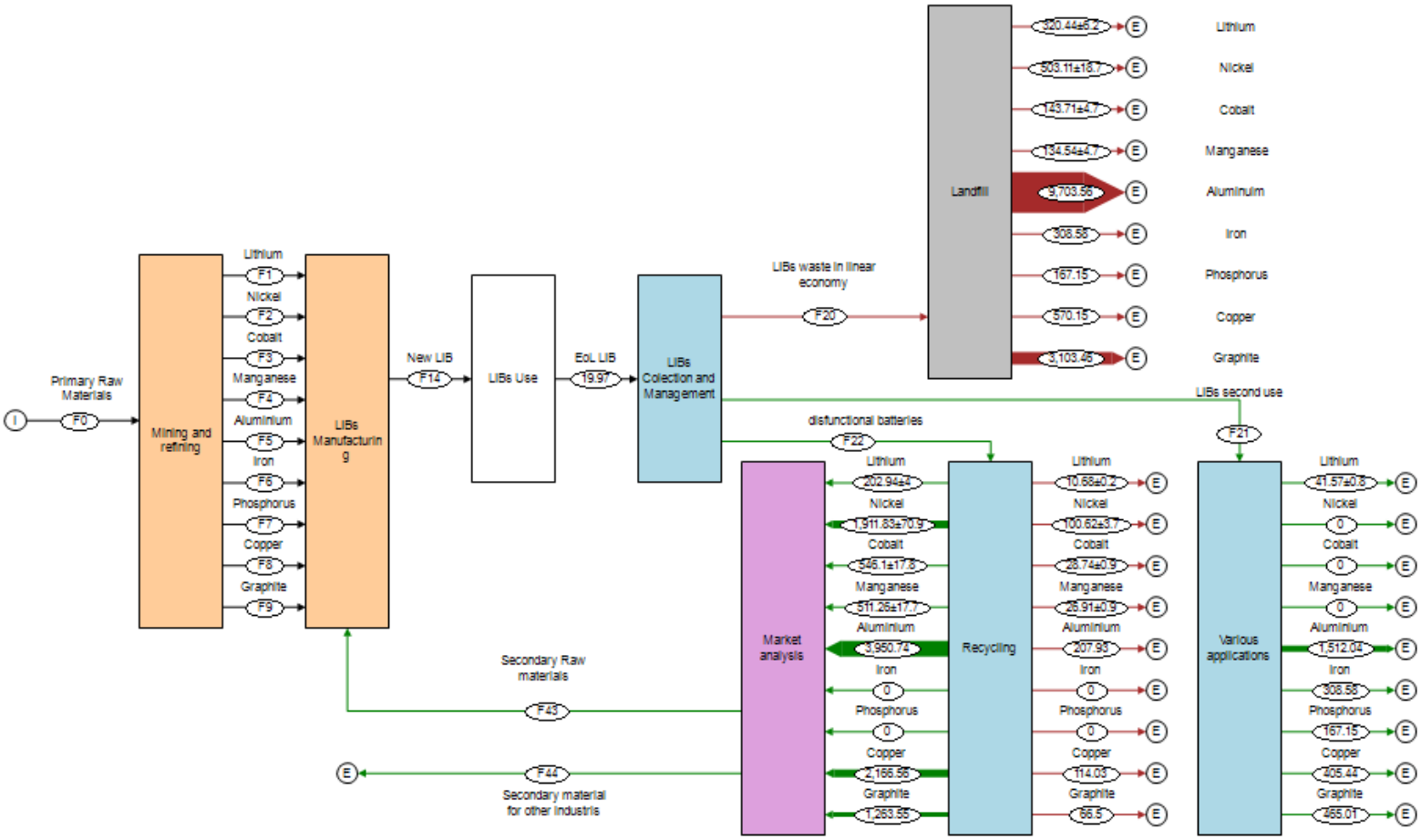
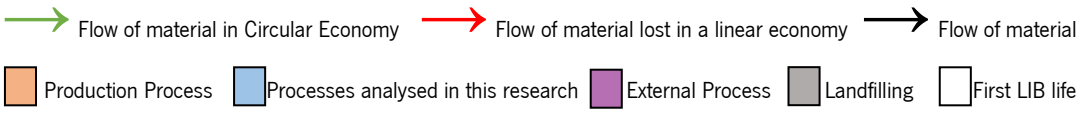


Figure 16: Sankey diagram – pessimistic scenario



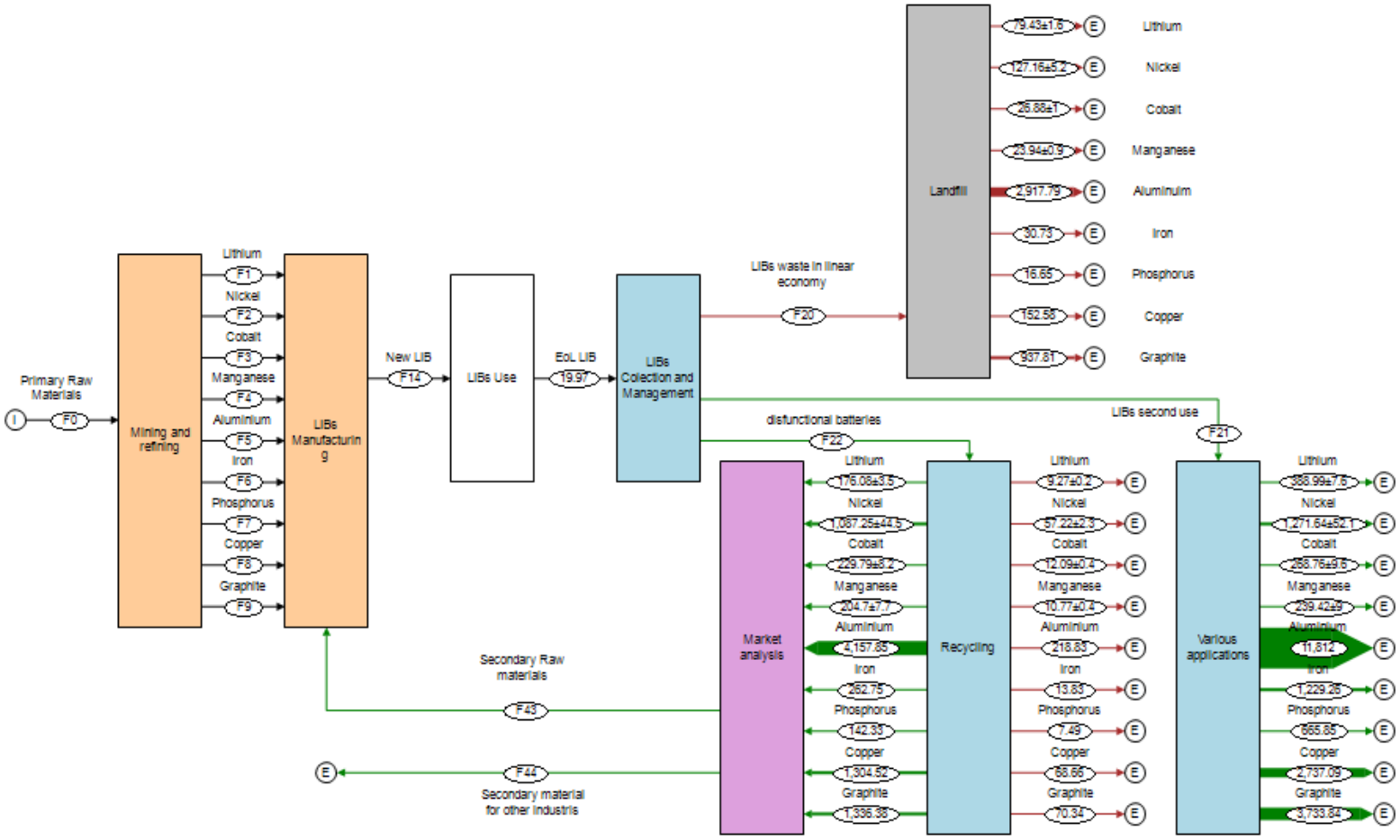


Figure 17: Sankey diagram – expected scenario

Flow of material in Circular Economy | Flow of material lost in a linear economy | Flow of material

Production Process | Processes analysed in this research | External Process | Landfilling | First LIB life

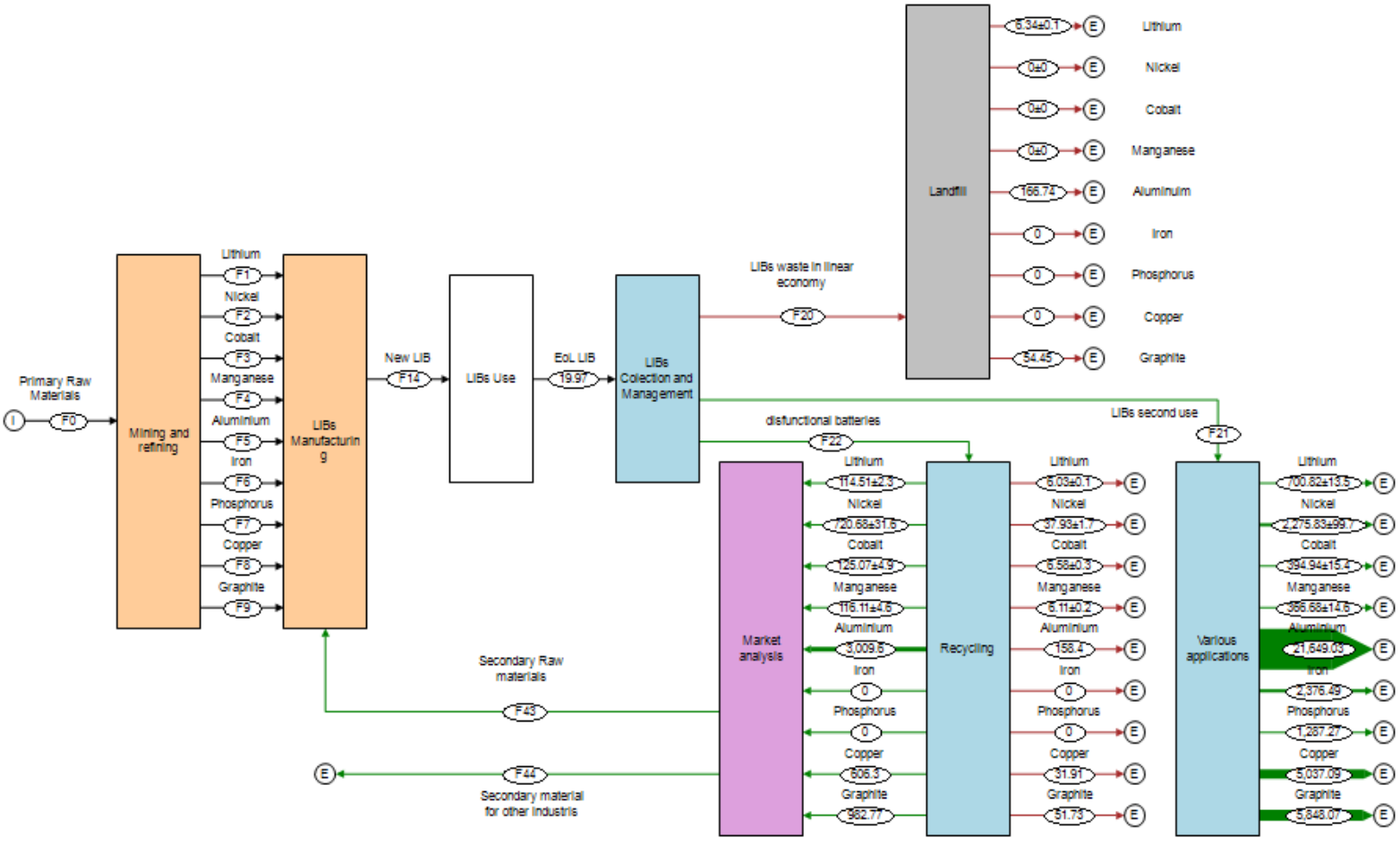


Figure 18: Sankey diagram – optimistic scenario

Flow of material in Circular Economy
Flow of material lost in a linear economy
Flow of material
Production Process
Processes analysed in this research
External Process
Landfilling
First LIB life

The width of the arrows allows us to have a perception of the proportion of different materials between each other. So, the larger the arrow the higher the quantity of material. For being used in larger quantities Al, Cu, and Gr stand out compared to the rest of the materials. This is because Al and Cu are used in several components of the battery such as module and battery enclosures, thermal conductors, terminals, and cell current collectors. As for Gr, since it is the main material used in the anode part of the battery (previously it was explained that Si started to be integrated into the anode part of the battery but the material was not considered in the work), it also presents large amounts. Even though it is possible to observe the considerable difference in the material utilization between these three materials and the rest, it is not possible to get a visual idea of the proportions used in the materials that constitute the cathode part of the battery namely Li, Ni, Co,

Mn, Fe, and P for having lower quantities. Nevertheless, the quantities of these materials are presented in each respective arrow and were discussed in detail in Chapter 4.1. Moreover, with these diagrams, it is intended to have an overall overview of all materials studied.

In the pessimistic scenario, it is seen that Al and Gr stand out in the flow of materials that are disposed of, and this is due to the fact that in this scenario these materials present recycling rates of 30% each. Regarding the processes that are in line with circularity (recycling and reuse), it is seen that very few materials are used in second lives and some material is recycled, in particular, Ni which has a recycling rate of 80% in this scenario. As for the expected scenario, it is observed a considerable decrease in material disposed of, and with reuse rates of 50% for NMC and NCA, and 80% for LFP batteries the flow of materials in second life is much higher compared to the pessimistic scenario, again with Al, Cu, and Gr standing out. Lastly, the optimistic scenario presents visually a similar diagram as the expected scenario since both embrace reuse of LIB, however in the optimistic it is noted an even higher amount of materials reused, decreasing the flow of material that is recycled. Once more, in this scenario, there is a lower amount of material recycled due to the fact that more LIB are reused in the grid, postponing the process of recycling. In this scenario's diagram, it is also verified that the flow of materials disposed of is insignificant, since in this scenario only some Li, Al, and Gr are lost directly in a linear economy.

4.3 Solutions for Lithium-ion batteries management with a sustainable and circular perspective

In this chapter, the solutions for the circularity of LIB are recapitulated and some other solutions are identified. Not all possible solutions were analysed in this work, so it is crucial to describe which other solutions play an important role in the future of batteries and contextualize them in this research.

Solutions analysed in this study

The first solution analysed is the responsible choice of materials used in batteries. When manufacturing batteries, it is important to take into consideration the materials that are used, understand the impact of their use, and identify which represent a more sustainable use of materials. In this work, this was reflected in the market share of battery chemistries, as for the three scenarios different market shares of different battery chemistries were considered, having as the main focus the Co utilization in these battery chemistries. This material not only is toxic to the environment but also presents some barriers to social sustainability given the poor conditions of

its exploitation in the Democratic Republic of the Congo, and the health risks that it presents. Moreover, because of its unstable supply and high prices, it presents also challenges to economic sustainability. For this reason, it was identified that battery chemistries with lower Co content are more sustainable. For the optimistic scenario, this solution was considered and the results were compared with other scenarios. In future research, it would also be interesting to study more in-depth the impact of other materials.

Another solution is to improve the longevity of batteries with new technologies and innovations. In this research, specific innovations or improvements were not explained but it was considered that over the years there is an increase in the battery lifetime. Improving this feature in batteries allows EVs to have longer lifetimes and decreases the pressure in the production of new batteries. In a circular economy, products are not intended to have short lifetimes, but on the other hand to present durability and longevity. In a linear economy, products are not designed to last, which stimulates consumerism, an increasing consumption of goods which results in the over-exploration of goods, and an increase in waste. That is why, improving the lifetime of batteries is in line with the circular economy.

The third solution studied in this work is the reuse of LIB. There are several applications where LIB from retired EVs can be applied, and giving a second life for these batteries not only prolongs their lifetime and postpones their EoL management, but also substitutes new batteries that would be produced for these other applications. In this work, it was assessed the use of these batteries in the grid, for the storage of energy produced by solar, wind, and hydro energy sources. Nevertheless, there are many other possible applications such as storing domestic energy (produced by renewable energies installed in homes) and energy produced by renewables installed in companies and other commercial and industrial buildings. There is also the possibility of using these batteries in EVs that require lower energy-intensive batteries and in UPS (uninterruptable power supply) systems that provide backup power to electrical systems. Note that, the utilization of LIB in the grid has shown great potential in this research.

Finally, the fourth solution considered in this work is recycling, one of the most important activities in a circular economy, and the last solution before incineration and disposal of waste. Recycling involves several processes that allow the recovery of material so it can be again used for manufacturing. As explained throughout this work the secondary material obtained from recycling can then be used again in the LIB industry, closing the loop, or in other industries that use these

materials. It is important to mention that this solution still needs a lot of improvement in the techniques used and in the way this business is done. This work concludes that even though there is a considerable economic value of materials in EoL there are still some barriers in recycling LIB. Business models that recycle and recover materials with profit and in a sustainable way need collaboration between investigation, companies, and governments. Investigation and academic research bring innovation and solutions to the industry. Governments play a crucial role with the application of laws that promote recycling, reusing, and other circularity practices. Lastly, companies implement the solutions in the real world and obtain the results desired.

Other solutions

There are other solutions that were not applied in this study and allow efficient management of LIB during their lifetime and in EoL promoting circularity and sustainability. One solution is product design where LIB are designed and manufactured in a way that simplifies and encourages the processes of dismantling, repairing, remanufacturing, reconfiguration (in the case of reuse in a different application), repacking, and recycling. Products should be conceived having in mind their management and facilitating practices of a circular economy and Harper et al., (2023) explore the concept of battery design, the current status, and challenges. Another solution not considered in this research is the identification of batteries with Battery Passports, a solution that the EU is committed to. The EU battery regulation requires all EV batteries sold into the EU market to have a unique battery passport from 2027 in the form of a QR code (European Commission, 2023). Battery Passports should include information regarding the battery's main characteristics such as battery capacity, material used, and others, which enables an appropriate management of batteries during their lifetime and in EoL.

4.4 Limitations of the study

The main limitation of this work includes the fact that results were obtained from predictions, assumptions, and data that could be more precise. The limitations related to each variable considered in the work were exposed throughout the work. This limitation is due to the fact that LIB are a technology that is in constant development, so features and characteristics of batteries are being continuously improved and modified. For this reason, the several sources analysed in this work indicate slightly different values and make different assumptions, making it difficult to understand which are the more real and accurate values. It is crucial to develop research with

more accurate data to achieve results that provide better insights into the waste management system of LIB.

Another limitation of this work is the fact that the batteries and their materials used in a second life (in the grid) were not considered in the process of recycling. As explained in the work it was only considered the management of batteries after being used in EVs. Therefore, after being reused, batteries should undergo the process of collection and management to understand what is their future path. If reused one more time in another application, if recycled, or if disposed of. For example, in the optimistic scenario of this work, if it would be considered in the recycling process also the batteries that reach their EoL after being used in the grid, much higher proportions of recycled material would be achieved.

Lastly, a limitation that also compromises the accuracy of this work's results is the fact that the research was developed for the CZ, and there was limited research specifically for this country. Most of the research regarding LIB focuses on countries like the USA and China, so some data that was used in this work was regarding the characteristics and the production of LIB in these countries and the industry may be slightly different in Europe and specifically in the CZ.

5 Conclusions and future research

Considering the decarbonization targets of the EU and the CZ in the energy transition, and the fact that the most popular car in the CZ (Škoda Auto) is committed to a sustainable future where EVs are at the core of their business, it is clear that EV sales in the country are expected to grow in future years, meaning an increase in EOL LIB in future years. Therefore, the country needs to assess solutions that embrace the circularity of materials used in these batteries, and for that reason, a MFA was developed in this work for LIB with a circular economy perspective. Not only solutions that promote the circularity of materials were studied but also the impact of LIB use is assessed. The number of batteries reaching EoL in the following years was estimated and then determined in which proportion the materials were recycled and disposed of. Moreover, the potential for the second use of batteries in the energy grid was assessed.

The first conclusion of this research is that CZ needs to accelerate the energy transition so that it can achieve its goals regarding decarbonization. Both RES and EVs play an important role in decarbonization and taking into account the EV sales trend, and the several sources considered regarding RES, it is concluded that the country is far from achieving the goal of 44000 annual EV sales by 2030, and the goal of 30% share of energy production by RES.

Regarding the question "*How circular waste management can support the sustainability of lithium-ion batteries?"* stated at the beginning of this work, the results obtained in this research and the identified solutions allowed to show the relevance of circularity for a LIB suitability as summarized below.

Regarding the reuse of LIB, the calculations made in the MFA of this research prove that the optimistic scenario is the scenario with a higher potential for the second use of LIB in the grid, specifically for the storage of energy produced by RES. In this scenario, the capacity available from batteries to store energy exceeds the annual expected electricity production by wind energy in all years from 2044 to 2050, and by hydro energy from 2041 to 2050, except 2042. Moreover, in this scenario in 2047, the higher contribution from batteries to the store of energy is achieved, with 3849 GWh of capacity available representing 26.68% of the total energy expected to be produced in this year by all wind, hydro, and solar renewable sources. On the other hand, in the same year, for pessimistic and expected scenarios respectively only 1.76% and 14.51% of the energy produced by the 3 RES, is expected to be stored by retired LIB from EVs. Therefore, the reuse of batteries in the grid represents a great opportunity and a circular solution where the full potential of batteries

and their materials is explored. Furthermore, some obstacles in the reuse of batteries were identified such as possible battery cell failures, technical limits, and economic uncertainty due to the costs involved in all processes of repurposing the batteries such as the cost of disassembling, testing, and repackaging. So, even though LIB reuse presents a great opportunity for a circular economy in the LIB industry, more research is necessary, so the challenges are overcome.

Concerning the LIB recycling studied in this work, it is important to note that even though the optimistic scenario is the scenario that presents higher recycling efficiencies and is closest to circular concepts, it only presents significant and considerable amount of material recycled around 2040. This means that until this year the material demand is mostly satisfied with primary material from mining. In this scenario, in 2030, the amount of Co and Mn that is satisfied with material recycled is 4.37% and 4.01% respectively (two higher CMURs of all materials in this scenario for 2030). It is clear that regardless of how circular the LIB industry is, in the short term (more or less 15 years) the increasing demand for EVs, and the materials used in their batteries, have to be satisfied with primary material, and mining activities will increase considerably since the material recycled is only available in later years. Nevertheless, in the long term, after 2040, an efficient and technologically advanced recycling industry can result in a great positive impact with regard to how the materials are explored and managed. Moreover, the recycling rates assumed in the scenarios of this work have in count the scientific potential, and in the real world, recycling efficiencies are mostly dictated by economic feasibility. Constant developments and changes in the EV market can also present a challenge for the LIB recycling industry since recycling companies have to adapt to these changes. So, it is concluded that not only do recycling companies have to be flexible, so they can adapt to the market and achieve greater recycling efficiencies, but also governments have to facilitate and create conditions that allow these companies to continuously develop an economically viable business. Furthermore, a lot of work still has to be done with research, and development so recycling techniques are improved and easier and cheaper processes of recycling are obtained.

In future research, it would be important to explore and study separately more in detail the recycling process, other second-use applications, and the several variables considered in this work. The goal of this work was to have a more general idea of the LIB industry in CZ and present possible solutions for the management of EoL LIB. It can, and should, be explored more in detail all the variables and matters of this industry so practical and real solutions can be applied in the industry. It is also recommended to calculate the costs involved in recycling materials and compare them to their economic value to understand how profitable it would be to recycle them. Also, it would be

interesting to calculate the total CO2 emissions in the LIB and EVs lifecycle including production and recycling, and compare them with the total emissions of normal combustion vehicles so the real difference in emissions between the two vehicles is compared. Finally, an assessment of the country's potential for recycling and mining should be done to understand the potential that the country has to offer raw materials for the production of batteries since Škoda is producing their own batteries and the production is expected to grow in future years. This way it could be realized how many new jobs could be created in the country and in which proportion the country could reduce importation for this industry.

In this research, the MFA method has proven to be a valuable tool for the quantification of materials and is recommended to be used in the several other industries involved in the energy transition to find solutions that are in line with the circular economy and sustainable practices.

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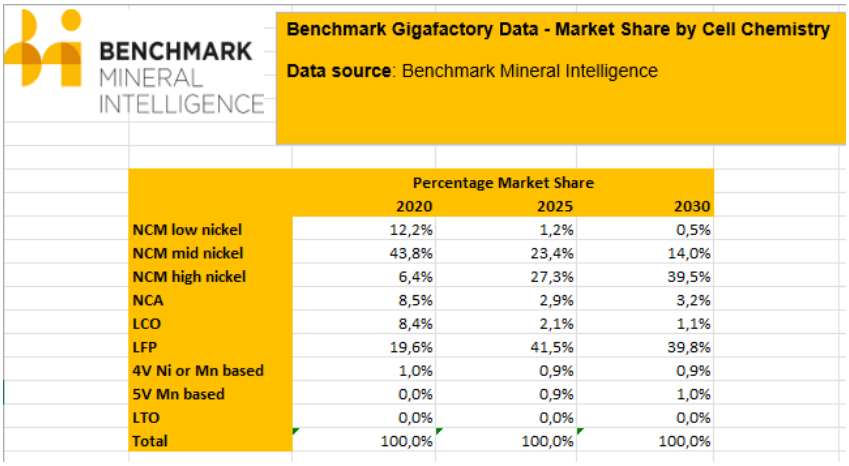
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Appendix

Appendix A - Market share by cell chemistry provided by Benchmark Mineral Intelligence



Benchmark Gigafactory Data - Market Share by Cell Chemistry

Data source: Benchmark Mineral Intelligence

	Percentage Market Share		
	2020	2025	2030
NCM low nickel	12,2%	1,2%	0,5%
NCM mid nickel	43,8%	23,4%	14,0%
NCM high nickel	6,4%	27,3%	39,5%
NCA	8,5%	2,9%	3,2%
LCO	8,4%	2,1%	1,1%
LFP	19,6%	41,5%	39,8%
4V Ni or Mn based	1,0%	0,9%	0,9%
5V Mn based	0,0%	0,9%	1,0%
LTO	0,0%	0,0%	0,0%
Total	100,0%	100,0%	100,0%

Appendix B – Materials demand from 2018 to 2030

B.1 - Pessimistic Scenario

Demand for each material in (kg)													
Year	Mass of Li	Standard Error Li (±)	Mass of Ni	Standard Error Ni (±)	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2010	9	0	32	1	22	1	18	0	217	1	1	46	69
2011	87	2	294	8	207	6	172	4	2023	10	5	432	645
2012	141	3	478	14	336	9	280	7	3287	16	9	702	1048
2013	70	2	236	7	166	4	138	3	1626	8	4	347	518
2014	336	8	1140	33	800	21	667	17	7839	39	21	1673	2499
2015	1228	29	5796	182	2311	66	1656	47	30533	0	0	6201	9881
2016	990	23	4672	146	1863	53	1335	38	24614	0	0	4999	7965
2017	1463	34	6902	216	2752	78	1972	56	36357	0	0	7384	11766
2018	2657	62	12537	393	4999	142	3582	101	66044	0	0	13413	21373
2019	3070	72	14172	444	5645	160	4052	114	77070	495	268	15809	24899
2020	17739	352	69535	2620	18702	612	16432	571	500305	33925	18376	110420	159016
2021	15097	300	59243	2232	15932	521	13998	486	425660	28784	15591	93917	135297
2022	22383	443	85578	3220	23072	755	20296	705	635453	45717	24763	141178	201750
2023	37592	746	147164	5545	39586	1295	34783	1209	1060629	72158	39085	234171	337088
2024	29450	585	115260	4343	31005	1015	27243	947	830949	56565	30640	183472	264088
2025	46962	902	211116	7860	60399	1971	57744	2014	1236874	40356	21860	258802	394312
2026	55452	1065	249282	9281	71319	2328	68183	2378	1460478	47652	25812	305588	465596
2027	65472	1257	294325	10958	84205	2748	80503	2807	1724371	56262	30475	360805	549725
2028	77327	1485	347619	12943	99453	3246	95080	3315	2036611	66450	35994	426138	649266
2029	85082	1634	382484	14241	109427	3571	104616	3648	2240877	73115	39604	468878	714385
2030	113032	2168	507704	18788	146356	4764	139959	4878	2972496	95611	51789	621812	947345

B.2 - Expected Scenario

Demand for each material in (kg)													
Year	Mass of Li	Standard Error Li (±)	Mass of Ni	Standard Error Ni (±)	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2010	9	0	32	1	22	1	18	0	217	1	1	46	69
2011	87	2	294	8	207	6	172	4	2023	10	5	432	645
2012	141	3	478	14	336	9	280	7	3287	16	9	702	1048
2013	70	2	236	7	166	4	138	3	1626	8	4	347	518
2014	336	8	1140	33	800	21	667	17	7839	39	21	1673	2499
2015	1228	29	5796	182	2311	66	1656	47	30533	0	0	6201	9881
2016	990	23	4672	146	1863	53	1335	38	24614	0	0	4999	7965
2017	1463	34	6902	216	2752	78	1972	56	36357	0	0	7384	11766
2018	2657	62	12537	393	4999	142	3582	101	66044	0	0	13413	21373
2019	3068	71	14134	443	5632	160	4040	114	77103	542	293	15831	24907
2020	17736	352	69479	2618	18684	611	16414	570	500353	33993	18413	110452	159027
2021	15095	300	59206	2231	15920	521	13986	486	425691	28829	15616	93938	135305
2022	22365	443	85173	3207	22939	750	20167	701	635804	46212	25032	141413	201836
2023	37586	746	147017	5540	39537	1294	34736	1207	1060757	72338	39183	234256	337119
2024	40782	809	158445	5969	42626	1395	37456	1301	1153104	79963	43313	255116	366361
2025	59799	1170	232249	9777	44295	1646	40040	1555	1767797	149184	80808	395671	562483
2026	68689	1343	266755	11230	50877	1891	45990	1786	2030649	171390	92836	454512	646116
2027	77579	1517	301260	12682	57458	2136	51939	2017	2293502	193597	104865	513353	729749
2028	86469	1691	335765	14135	64040	2380	57889	2248	2556354	215803	116893	572194	813382
2029	95360	1865	370271	15587	70622	2625	63838	2479	2819206	238010	128922	631035	897014
2030	122258	2391	471439	19727	91423	3374	82523	3190	3613662	306645	166100	809885	1149310

B.3 - Optimistic Scenario

Demand for each material in (kg)													
Year	Mass of Li	Standard Error Li (±)	Mass of Ni	Standard Error Ni (±)	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2010	9	0	32	1	22	1	18	0	217	1	1	46	69
2011	87	2	294	8	207	6	172	4	2023	10	5	432	645
2012	141	3	478	14	336	9	280	7	3287	16	9	702	1048
2013	70	2	236	7	166	4	138	3	1626	8	4	347	518
2014	336	8	1140	33	800	21	667	17	7839	39	21	1673	2499
2015	1228	29	5796	182	2311	66	1656	47	30533	0	0	6201	9881
2016	990	23	4672	146	1863	53	1335	38	24614	0	0	4999	7965
2017	1463	34	6902	216	2752	78	1972	56	36357	0	0	7384	11766
2018	2657	62	12537	393	4999	142	3582	101	66044	0	0	13413	21373
2019	3066	71	14096	442	5619	160	4028	114	77136	588	319	15853	24915
2020	17734	352	69424	2616	18665	611	16397	570	500401	34060	18449	110484	159039
2021	15094	300	59170	2230	15908	521	13974	486	425723	28874	15640	93960	135313
2022	22348	443	84769	3194	22805	746	20039	696	636155	46707	25300	141647	201922
2023	37580	746	146869	5535	39488	1292	34689	1205	1060885	72518	39280	234341	337150
2024	45096	895	176243	6642	47386	1551	41627	1446	1273062	87021	47136	281209	404580
2025	65804	1267	238290	10824	35189	1478	33742	1421	2016070	202983	109949	460428	640438
2026	78964	1521	285948	12989	42227	1774	40491	1705	2419284	243579	131939	552513	768525
2027	94757	1825	343137	15587	50673	2128	48589	2046	2903140	292295	158327	663016	922230
2028	113709	2190	411764	18705	60807	2554	58307	2455	3483768	350754	189992	795619	1106676
2029	136450	2628	494117	22446	72969	3065	69968	2946	4180522	420905	227990	954743	1328011
2030	190126	3659	678523	30741	101395	4235	97227	4077	5835132	596142	322910	1336309	1852466

Appendix C – Amount of EoL LIB materials from 2018 to 2050

C.1 - Pessimistic scenario

	Mass of each material that composes EoL LIB (kg)												
Year	Mass of Li	Standard Error Li	Mass of Ni	Standard Error Ni	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2018	9	0	32	1	22	1	18	0	211	0	0	45	67
2019	85	2	294	8	207	6	172	4	1974	0	0	419	630
2020	139	3	478	14	336	9	280	7	3207	0	0	680	1023
2021	69	2	236	7	166	4	138	3	1586	0	0	336	506
2022	331	7	1140	33	800	21	667	17	7648	0	0	1622	2441
2023	1228	29	5796	182	2311	66	1656	47	30533	0	0	6201	9881
2024	990	23	4672	146	1863	53	1335	38	24614	0	0	4999	7965
2025	1464	34	6902	216	2752	78	1972	56	36407	10	5	7397	11781
2026	2659	62	12537	393	4999	142	3582	101	66125	16	9	13435	21397
2027	3003	70	14172	444	5645	160	4052	114	74643	0	0	15158	24152
2028	5	0	0	0	0	0	0	0	191	39	21	51	59
2029	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	13168	268	69535	2620	18702	612	16432	571	334070	0	0	65846	107892
2031	11219	229	59243	2232	15932	521	13998	486	284618	0	0	56098	91921
2032	16224	330	85578	3220	23072	755	20296	705	411439	0	0	81111	132857
2033	27938	569	147164	5545	39586	1295	34783	1209	709484	495	268	140014	229096
2034	21829	445	115260	4343	31005	1015	27243	947	553778	0	0	109152	178847
2035	0	0	0	0	0	0	0	0	0	0	0	0	0
2036	4571	84	0	0	0	0	0	0	166235	33925	18376	44574	51124
2037	45403	873	211116	7860	60399	1971	57744	2014	1180169	28784	15591	243597	376873
2038	55191	1060	249282	9281	71319	2328	68183	2378	1450997	45717	24763	303046	462681
2039	67613	1296	294325	10958	84205	2748	80503	2807	1802259	72158	39085	381690	573678
2040	75995	1460	347619	12943	99453	3246	95080	3315	1988177	56565	30640	413151	634371
2041	75232	1453	382484	14241	109427	3571	104616	3648	1882615	0	0	372813	604206
2042	0	0	0	0	0	0	0	0	0	0	0	0	0
2043	5437	100	0	0	0	0	0	0	197746	40356	21860	53024	60815
2044	106570	2049	507704	18788	146356	4764	139959	4878	2737496	47652	25812	558799	875074
2045	7580	139	0	0	0	0	0	0	275685	56262	30475	73922	84784
2046	8952	164	0	0	0	0	0	0	325605	66450	35994	87308	100136
2047	9850	181	0	0	0	0	0	0	358262	73115	39604	96065	110180
2048	0	0	0	0	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0	0	0	0	0
2050	12881	236	0	0	0	0	0	0	468495	95611	51789	125623	144081

C.2 - Expected scenario

	Mass of each material that composes EoL LIB (kg)												
Year	Mass of Li	Standard Error Li	Mass of Ni	Standard Error Ni	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2018	9	0	32	1	22	1	18	0	211	0	0	45	67
2019	85	2	294	8	207	6	172	4	1974	0	0	419	630
2020	139	3	478	14	336	9	280	7	3207	0	0	680	1023
2021	69	2	236	7	166	4	138	3	1586	0	0	336	506
2022	331	7	1140	33	800	21	667	17	7648	0	0	1622	2441
2023	1228	29	5796	182	2311	66	1656	47	30533	0	0	6201	9881
2024	990	23	4672	146	1863	53	1335	38	24614	0	0	4999	7965
2025	1464	34	6902	216	2752	78	1972	56	36407	10	5	7397	11781
2026	2659	62	12537	393	4999	142	3582	101	66125	16	9	13435	21397
2027	2995	70	14134	443	5632	160	4040	114	74448	0	0	15119	24090
2028	5	0	0	0	0	0	0	0	191	39	21	51	59
2029	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	13157	268	69479	2618	18684	611	16414	570	333787	0	0	65789	107802
2031	11211	228	59206	2231	15920	521	13986	486	284429	0	0	56060	91861
2032	16139	329	85173	3207	22939	750	20167	701	409365	0	0	80695	132197
2033	27914	569	147017	5540	39537	1294	34736	1207	708957	542	293	139924	228926
2034	30009	612	158445	5969	42626	1395	37456	1301	761286	0	0	150054	245862
2035	0	0	0	0	0	0	0	0	0	0	0	0	0
2036	4580	84	0	0	0	0	0	0	166566	33993	18413	44663	51226
2037	43584	872	232249	9777	44295	1646	40040	1555	1178059	28829	15616	237538	381115
2038	51825	1034	266755	11230	50877	1891	45990	1786	1417277	46212	25032	290042	457480
2039	61243	1218	301260	12682	57458	2136	51939	2017	1699332	72338	39183	354032	547018
2040	68169	1355	335765	14135	64040	2380	57889	2248	1890736	79963	43313	393715	608678
2041	63294	1277	370271	15587	70622	2625	63838	2479	1652959	0	0	318317	538347
2042	0	0	0	0	0	0	0	0	0	0	0	0	0
2043	20098	369	0	0	0	0	0	0	731000	149184	80808	196011	224812
2044	104036	2056	471439	19727	91423	3374	82523	3190	2950911	171390	92836	632174	945488
2045	26082	478	0	0	0	0	0	0	948624	193597	104865	254365	291739
2046	29073	533	0	0	0	0	0	0	1057436	215803	116893	283541	325203
2047	32065	588	0	0	0	0	0	0	1166248	238010	128922	312718	358667
2048	0	0	0	0	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0	0	0	0	0
2050	41312	758	0	0	0	0	0	0	1502562	306645	166100	402898	462098

C.3 - Optimistic scenario

	Mass of each material that composes EoL LIB (kg)												
Year	Mass of Li	Standard Error Li	Mass of Ni	Standard Error Ni	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2018	9	0	32	1	22	1	18	0	211	0	0	45	67
2019	85	2	294	8	207	6	172	4	1974	0	0	419	630
2020	139	3	478	14	336	9	280	7	3207	0	0	680	1023
2021	69	2	236	7	166	4	138	3	1586	0	0	336	506
2022	331	7	1140	33	800	21	667	17	7648	0	0	1622	2441
2023	1228	29	5796	182	2311	66	1656	47	30533	0	0	6201	9881
2024	990	23	4672	146	1863	53	1335	38	24614	0	0	4999	7965
2025	1464	34	6902	216	2752	78	1972	56	36407	10	5	7397	11781
2026	2659	62	12537	393	4999	142	3582	101	66125	16	9	13435	21397
2027	2987	70	14096	442	5619	160	4028	114	74253	0	0	15080	24028
2028	5	0	0	0	0	0	0	0	191	39	21	51	59
2029	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	13145	268	69424	2616	18665	611	16397	570	333505	0	0	65732	107712
2031	11204	228	59170	2230	15908	521	13974	486	284241	0	0	56023	91801
2032	16055	327	84769	3194	22805	746	20039	696	407290	0	0	80279	131537
2033	27889	568	146869	5535	39488	1292	34689	1205	708430	588	319	139834	228756
2034	33372	680	176243	6642	47386	1551	41627	1446	846658	0	0	166873	273444
2035	0	0	0	0	0	0	0	0	0	0	0	0	0
2036	4589	84	0	0	0	0	0	0	166896	34060	18449	44752	51327
2037	42347	837	238290	10824	35189	1478	33742	1421	1162937	28874	15640	231668	378065
2038	52441	1034	285948	12989	42227	1774	40491	1705	1454610	46707	25300	293845	471850
2039	65148	1282	343137	15587	50673	2128	48589	2046	1826230	72518	39280	374252	591037
2040	78178	1538	411764	18705	60807	2554	58307	2455	2191477	87021	47136	449103	709245
2041	79745	1588	494117	22446	72969	3065	69968	2946	2118087	0	0	401720	693731
2042	0	0	0	0	0	0	0	0	0	0	0	0	0
2043	27346	502	0	0	0	0	0	0	994616	202983	109949	266697	305884
2044	142628	2787	678523	30741	101395	4235	97227	4077	4107576	243579	131939	873081	1321174
2045	39379	722	0	0	0	0	0	0	1432247	292295	158327	384043	440473
2046	47254	867	0	0	0	0	0	0	1718696	350754	189992	460852	528567
2047	56705	1040	0	0	0	0	0	0	2062435	420905	227990	553023	634281
2048	0	0	0	0	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0	0	0	0	0
2050	80314	1473	0	0	0	0	0	0	2921094	596142	322910	783264	898352

Appendix D – Installed generation capacity (2020-2030) taken from the National Energy and Climate Plan of the Czech Republic

Installed generation capacity (MWe)	**2016**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Biomass	376	414	414	414	431	431	435	435	436	436	436	454
Hydropower plants	1 090	1 106	1 109	1 111	1 113	1 115	1 117	1 119	1 121	1 123	1 125	1 127
Biodegradable component of MSW	55	55	102	112	123	133	133	133	133	154	154	154
Biogas stations	369	355	354	345	339	338	337	322	314	307	299	287
Geothermal energy	0	10	10	10	10	10	10	10	10	10	10	10
Wind power plants	282	370	410	455	505	565	625	685	745	820	895	970
Photovoltaic systems	2 068	2 082	2 153	2 236	2 340	2 470	2 628	2 822	3 051	3 319	3 625	3 975
Total	4 240	4 392	4 552	4 683	4 861	5 062	5 285	5 526	5 810	6 169	6 544	6 977

Appendix E – Material recycled from 2018 to 2050 in kg

E.1 – Pessimistic scenario

	Mass of each material recycled (kg)												
Year	Mass of Li	Standard Error Li	Mass of Ni	Standard Error Ni	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2018	3,48	0	24	1	17	0	14	0	60	0	0	34	19
2019	32	1	224	6	157	4	131	3	562	0	0	318	180
2020	53	1	363	10	255	7	213	5	914	0	0	517	292
2021	26	1	180	5	126	3	105	3	452	0	0	256	144
2022	126	3	866	25	608	16	507	13	2180	0	0	1233	696
2023	467	11	4405	138	1757	50	1258	35	8702	0	0	4713	2816
2024	376	9	3551	111	1416	40	1014	29	7015	0	0	3799	2270
2025	556	13	5245	164	2092	59	1498	42	10369	0	0	5617	3355
2026	1010	24	9528	298	3800	108	2722	77	18834	0	0	10202	6095
2027	1141	27	10771	337	4290	122	3079	87	21273	0	0	11520	6883
2028	1	0	0	0	0	0	0	0	27	0	0	20	8
2029	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	5004	102	52846	1991	14213	465	12488	434	95210	0	0	50043	30749
2031	4263	87	45025	1697	12108	396	10638	370	81116	0	0	42635	26198
2032	6165	126	65039	2447	17535	573	15425	536	117260	0	0	61644	37864
2033	10604	216	111844	4214	30085	985	26435	919	201857	0	0	106163	65186
2034	8295	169	87598	3300	23564	771	20705	719	157827	0	0	82955	50971
2035	0	0	0	0	0	0	0	0	0	0	0	0	0
2036	868	16	0	0	0	0	0	0	23688	0	0	16938	7285
2037	16516	318	160448	5974	45904	1498	43885	1530	316250	0	0	170763	101228
2038	19802	381	189454	7054	54202	1769	51819	1807	381612	0	0	207490	122047
2039	23846	459	223687	8328	63996	2089	61182	2133	463260	0	0	254058	148003
2040	27430	528	264191	9836	75584	2467	72261	2520	527134	0	0	285753	168649
2041	28588	552	290688	10823	83165	2714	79508	2772	536545	0	0	283338	172199
2042	0	0	0	0	0	0	0	0	0	0	0	0	0
2043	1033	19	0	0	0	0	0	0	28179	0	0	20149	8666
2044	39277	756	385855	14279	111231	3621	106369	3707	746913	0	0	400895	239163
2045	1440	26	0	0	0	0	0	0	39285	0	0	28091	12082
2046	1701	31	0	0	0	0	0	0	46399	0	0	33177	14269
2047	1872	34	0	0	0	0	0	0	51052	0	0	36505	15701
2048	0	0	0	0	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0	0	0	0	0
2050	2447	45	0	0	0	0	0	0	66761	0	0	47737	20532

E.2 – Expected scenario

	Mass of each material recycled (Kg)												
Year	Mass of Li	Standard Error Li	Mass of Ni	Standard Error Ni	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2018	3	0	13	0	9	0	8	0	60	0	0	19	19
2019	28	1	126	4	88	2	74	2	562	0	0	179	180
2020	46	1	204	6	143	4	120	3	914	0	0	291	292
2021	23	1	101	3	71	2	59	1	452	0	0	144	144
2022	110	2	487	14	342	9	285	7	2180	0	0	693	696
2023	408	10	2478	78	988	28	708	20	8702	0	0	2651	2816
2024	329	8	1997	63	797	23	571	16	7015	0	0	2137	2270
2025	487	11	2950	92	1177	33	843	24	10367	2	1	3159	3355
2026	884	21	5360	168	2137	61	1531	43	18832	3	2	5738	6094
2027	996	23	6042	189	2408	68	1727	49	21218	0	0	6463	6866
2028	1	0	0	0	0	0	0	0	22	7	4	9	7
2029	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	4375	89	29702	1119	7987	261	7017	244	95129	0	0	28125	30724
2031	3728	76	25311	954	6806	223	5979	208	81062	0	0	23966	26180
2032	5366	109	36412	1371	9806	321	8622	300	116669	0	0	34497	37676
2033	9267	189	62850	2368	16902	553	14850	516	201599	93	50	59635	65104
2034	9978	203	67735	2552	18223	596	16013	556	216967	0	0	64148	70071
2035	0	0	0	0	0	0	0	0	0	0	0	0	0
2036	609	11	0	0	0	0	0	0	18988	5813	3149	7637	5840
2037	13717	276	99287	4180	18936	704	17117	665	311591	4930	2670	91832	101189
2038	15990	321	114038	4801	21750	808	19661	763	365203	7902	4280	108419	118473
2039	18419	369	128789	5422	24564	913	22204	862	423698	12370	6700	126970	137260
2040	20517	411	143540	6043	27377	1018	24748	961	471859	13674	7407	141365	152868
2041	21045	425	158291	6664	30191	1122	27291	1060	471093	0	0	136081	153429
2042	0	0	0	0	0	0	0	0	0	0	0	0	0
2043	2673	49	0	0	0	0	0	0	83334	25510	13818	33518	25629
2044	29985	599	201540	8433	39084	1442	35278	1364	697402	29308	15875	212494	225299
2045	3469	64	0	0	0	0	0	0	108143	33105	17932	43496	33258
2046	3867	71	0	0	0	0	0	0	120548	36902	19989	48486	37073
2047	4265	78	0	0	0	0	0	0	132952	40700	22046	53475	40888
2048	0	0	0	0	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0	0	0	0	0
2050	5494	101	0	0	0	0	0	0	171292	52436	28403	68896	52679

E.3 – Optimistic scenario

	Mass of each material recycled (Kg)												
Year	Mass of Li	Standard Error Li	Mass of Ni	Standard Error Ni	Mass of Co	Standard Error Co	Mass of Mn	Standard Error Mn	Mass of Al	Mass or Fe	Mass of P	Mass of Cu	Mass Gr
2018	0	0	7	0	5	0	4	0	48	0	0	11	15
2019	19	0	70	2	49	1	41	1	445	0	0	99	142
2020	31	1	114	3	80	2	66	2	724	0	0	162	231
2021	15	0	56	2	39	1	33	1	358	0	0	80	114
2022	75	2	271	8	190	5	159	4	1725	0	0	385	551
2023	277	6	1377	43	549	16	393	11	6889	0	0	1473	2229
2024	223	5	1110	35	443	13	317	9	5554	0	0	1187	1797
2025	330	8	1639	51	654	19	468	13	8203	0	0	1754	2655
2026	599	14	2978	93	1187	34	851	24	14901	0	0	3186	4822
2027	674	16	3348	105	1335	38	957	27	16753	0	0	3582	5421
2028	0	0	0	0	0	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	2966	60	16488	621	4433	145	3894	135	75247	0	0	15611	24302
2031	2528	52	14053	530	3778	124	3319	115	64132	0	0	13305	20713
2032	3622	74	20133	758	5416	177	4759	165	91895	0	0	19066	29678
2033	6275	128	34881	1315	9379	307	8239	286	159189	0	0	33027	51413
2034	7530	153	41858	1577	11254	368	9886	344	191027	0	0	39632	61696
2035	0	0	0	0	0	0	0	0	0	0	0	0	0
2036	0	0	0	0	0	0	0	0	0	0	0	0	0
2037	8677	173	56594	2571	8357	351	8014	337	230466	0	0	46011	75484
2038	10412	207	67913	3085	10029	421	9617	405	276559	0	0	55213	90580
2039	12495	249	81495	3702	12035	505	11540	486	331870	0	0	66256	108697
2040	14994	299	97794	4442	14442	607	13848	583	398244	0	0	79507	130436
2041	17993	358	117353	5331	17330	728	16617	700	477893	0	0	95408	156523
2042	0	0	0	0	0	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0	0	0	0	0	0
2044	24776	493	161149	7301	24081	1006	23092	968	657480	0	0	131348	215272
2045	0	0	0	0	0	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix F - Price of each material in USD per tonne. Values gathered from Trading Economics, Index Mundi, and BusinessAnalytiq on 27th May 2024.

Material	Price USD/tonne
Li	14562
Ni	20553
Co	27150
Mn	5620
Al	2738
Fe	118
P	153
Cu	10738
Gr	1120