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Critical Raw Materials and their Meaning for Value Chains in Europe

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Preface, Dedication, Acknowledgement

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Abstract

This thesis describes the importance of Critical Raw Materials and their value chain within the EU`s economy. Critical Raw Materials are crucial for the EU´s technological development. As Critical Raw Materials are always connected to a huge supply risk. This mentioned development could be in dange, if suppliers stop their imports into the EU.

This would result in a financial, technological and social disadvantage towards other modern industry states and it would decrease the EU´s competitiveness on worldwide trade markets.

The goal is to gain information through a literature review on how and where two Critical Raw Materials, namely lithium and cobalt could be extracted within the EU taking into account primary and secondary extraction. Furthermore, the goal is to identify opportunities for substituting these materials in their main areas of industrial application and to decrease dependency on import from non EU-countries.

As a result, substitution possibilities of lithium and cobalt in batteries are presented as well as possibilities to mine such raw materials within the EU. The substitution of lithium in batteries for example, can be proceeded with the non-Critical Raw Material sodium while the substitution of cobalt is already implemented with so called LFPs (Lithium-Iron-Phosphate-Battery). Further, huge mineable lithium and cobalt deposits such as the Iberia or the Kevitsa project are listed as primary raw materials suppliers within the EU.

The findings of this thesis help to support the EU´s way towards raw material independency on the world’s lithium and cobalt markets.

Zusammenfassung

Diese Arbeit beschreibt die Bedeutung von kritischen Rohstoffen und ihrer Wertschöpfungskette in der EU-Wirtschaft. Kritische Rohstoffe sind entscheidend für die technologische Entwicklung der EU. Da kritische Rohstoffe immer mit einem großen Versorgungsrisiko verbunden sind, könnte diese Entwicklung gefährdet sein, wenn die Lieferanten dieser Rohstoffe ihre Importe in die EU einstellen. Dies würde zu einer finanziellen, technologischen und sozialen Benachteiligung gegenüber anderen modernen Industriestaaten führen und die Wettbewerbsfähigkeit der EU auf den weltweiten Handelsmärkten verringern.

Ziel ist es, durch eine Literaturrecherche Informationen darüber zu gewinnen, wie und wo zwei Kritische Rohstoffe, Lithium und Kobalt, in der EU primär und sekundär gewonnen werden können und Möglichkeiten zur Substitution dieser in ihren Hauptanwendungsbereichen aufzuzeigen, um die Abhängigkeit von deren Import aus Nicht-EU-Staaten zu verringern.

Als Ergebnis werden Substitutionsmöglichkeiten für Lithium und Kobalt in Batterien sowie Möglichkeiten zum Abbau dieser Rohstoffe in der EU vorgestellt. Die Substitution von Lithium in Batterien kann z.B. mit dem nichtkritischen Rohstoff Natrium erfolgen, die Substitution von Kobalt wird bereits mit sogenannten LFPs (Lithium-Iron-Phosphate-Battery) umgesetzt. Zudem sind große, abbaubare Lithium- und Kobaltvorkommen wie das Iberia- oder das Kevitsa-Projekt als primäre Rohstofflieferanten in der EU gelistet.

Diese Erkenntnisse dieser Arbeit unterstützen den Weg der EU in Richtung Rohstoffunabhängigkeit auf den Weltmärkten für Lithium und Kobalt.

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1 Introduction and research method

In modern society, critical raw materials which are materials of high economical and strategical importance for the European but also pose a high risk concerning supply, such as cobalt and lithium are crucial for ensuring consistent industrial, technological, and ecological development. However, for the EU and industry there is one major problem: The EU is strongly dependent on non-EU states in terms of critical raw materials, especially cobalt and lithium. These two materials are crucial for achieveing a mobility change towards E-mobility, as they are essential for the battery industry. Furthermore, the glass and ceramic industry, superalloy industry and many others are strongly dependent on such raw materials. If the main non-EU suppliers can or do not want to fulfill the EU´s demand for these raw materials, further industrial development is not possible, as products such as batteries cannot be produced anymore. This could threaten the residents' wealth, the achievement of climate goals and the technological success of the EU.

For this reason, the goal of this thesis is to gain information about options that could enable the EU to become self-sufficient with the raw materials lithium and cobalt through both, primary and secondary ways. This thesis assesses why and how important cobalt, lithium, and their final products are within the European industry and also how they could be substituted by non-critical raw materials to reduce European dependency on the world's raw material markets and to secure a self-supply for the European industry.

To achieve this goal, literature research is conducted on the possibilities of primary and secondary extraction of lithium and cobalt within the EU, as well as options and new technologies for reducing demand for these raw materials within the industries that consume them the most. This work gives information on how we could substitute cobalt and lithium in various final products. Further it shows opportunities for the EU´s critical raw material self-supply and highlights the current technical and financial value of cobalt and lithium in various final products to gain information if a final products price can be argued by the price of cobalt and lithium which are built in it.

1.1 Research method

The web search engine Google was used to collect information and data for this thesis due to its wide reach and limited access to other search platforms.

A manual web search was conducted as a technique to investigate the research problems. This investigation method was an appropriate tool for gaining information from different types of online sources, which was the main goal of the research process.

Search terms such as “*lithium resources in Europe*”, “*how and where is lithium mining proceeded*”, “*possibilities to recycle lithium and cobalt out of batteries*”, “*how much lithium is contained in a battery*”, “*how and where does cobalt mining proceed*”, “*can cobalt be substituted in a battery*”, “*are there cobalt resources in the EU*” were used in order to find documents and online sources.

Hence, the used literature was mainly grey literature, including online industry reports and journals. This type of source was used to gain information about the industry concerning current possibilities and problems which the European industry is facing and to provide data from and for the industry.

A full-text analysis and snowballing were conducted to filter information from the conducted sources. Information was collected and combined in various chapters to enable the view of many different solution opportunities concerning the various research questions.

Further, academic publications and master’s theses were implemented to collect additional scientific information on the topics discussed in this thesis.

These methods were used, as there were not enough academic papers available to achieve the research goal of this thesis. Further, it was the goal to provide insights from the view of the European industry. Therefore, industry journals and papers were utilized as the main information source.

2 Lithium

In this chapter, the properties, mining, and extraction of lithium out of its primary and secondary raw materials are examined, including the environmental impact of those activities. Additionally, the physical and chemical properties of lithium, which are the reasons for the usage of lithium in final products, are investigated.

2.1 Lithium properties

Lithium is a chemical element with the ordinal number 3 and a molar mass of 6.94 [g•mol^{-1}] (Gellenbeck, 2021). It belongs to the group of alkali metals and has the lowest density under standard conditions, namely ρ = 0.53 [g•cm^{-3}]. Additionally, it disposes over the highest specific heat capacity of all solid elements (3,482 [J•kg^{-1}•K^{-1}]), the lowest ionic radius among the alkali metals and has the highest electric potential with a normal potential difference of -3.045 [V], whereby its great suitability as electrical energy storage results from (Gellenbeck, 2021). It has a Mohs hardness of 0.6 [-], which corresponds to the other alkali metals. Its melting point is 180.54 [°C], and its evaporation point lies at 1,342 [°C] (Gellenbeck, 2021).

2.2 Lithium raw material mining and extraction

Due to its high reactivity, Lithium never occurs in its elementary form but only in chemical agglomerations. If elementary lithium is exposed to dry air, it reacts to lithium nitride. If it is exposed to moist air, it reacts to lithium hydroxide (Bundesverband Geothermie, 2021). Lithium occurs in so-called mineralogical lithium ore resources and in lithium brines. These two forms of lithium-containing raw materials are the main deposits for lithium extraction in an industrial way. According to the newest data, about 60 [%] of the current lithium supply come from mineralogical ores and about 40 [%] from brines (Schmidt, 2022).

The countries with the largest lithium reserves – either in the form of mineralogical ore or brines – are Chile (8 Mt), Australia (2,7 Mt), Argentina (2 Mt) and China (1 Mt). In Europe, Portugal is the only country that owns small amounts of lithium reserves. However, the overall amount of worldwide lithium reserves are approximately 14 million tons estimated, based on the reserve numbers of the main producer countries (Volkswagen AG, n.d.).

The largest five producer countries share 98.7 [%] of the worldwide lithium production, which was 185,500 [t] in 2020 (Reichl, Schatz, 2022). The countries with the largest reserves were also the largest lithium producers. (Figure 1):

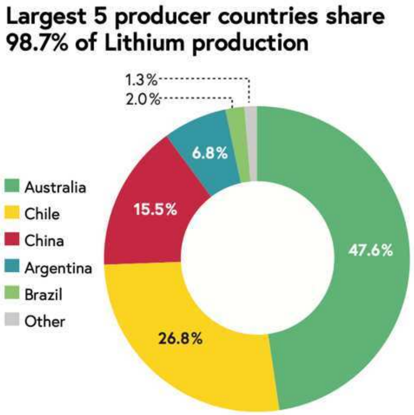


Figure 1: Lithium production per country and year (Reichl, Schatz, 2022)

2.2.1 Mineralogical lithium deposits

As already mentioned, lithium occurs mainly in two forms. One of them is the mineralogical form, where lithium occurs mainly as lithium pegmatites (Bundesverband Geothermie, 2021). Overall, there are over 200 minerals that contain lithium, but the most important minerals (Bundesverband Geothermie, 2021) which have an economically reasonable lithium content are:

Amblygonite	$LiAl[PO_4]F$
Lepidolith	$K(Li,Al)_3[(Al,Si)_4O_{10}](F,OH)_2$
Petalite	$LiAl[Si_4O_{10}]$
Spodumen	$LiAl[Si_2O_6]$

Of these minerals, amblygonite has the highest lithium content, which reaches up to 9 [%] (Bundesverband Geothermie, 2021), compared to kryolithionite, which has a lithium content of roughly 5.6 [%] (Schorn, 2022). However, kryolithionite ($Li_3Al_3[AlF_6]_2$) has the highest potential lithium content in absolute mass, which is about 20.82 [$g \bullet mol^{-1}$] (Schorn, 2022). Extracting lithium from ore is always associated with high costs. One cost driver is the expensive mining of the ore, as it is found and mined out of hard rock formations. Energy and chemicals that are needed for material processing are also relevant cost drivers. Due to these facts, mining for lithium ores is less economical than extracting lithium from brines, even though the ore has a higher lithium content then the brine in most cases („What is lithium extraction“, 2018). Nevertheless, 60 [%] of the produced lithium comes from mined ores. The processing of these depends strongly on the occurrence, mineralogy and further use of the concentrate (Schmidt, 2017). In general, the process entails removing the mineral material from the earth and then heating and pulverizing it. The crushed mineral powder is combined with chemical reactants, such as sulfuric acid. Then the slurry is heated, filtered and concentrated through an evaporation process to form saleable lithium carbonate, while the resulting wastewater is treated for reuse or disposal („What is lithium extraction“, 2018).

2.2.1.1 Spodumene processing

In order to ensure a better understanding of how complex the processing of lithium ores can be, the processing of spodumene, which is mainly mined in Australia, is explained in detail in this chapter.

The first process is the so-called Acid-Roast-Process, which is a very common lithium processing method in China (Schmidt, 2017). In this process, the spodumene gets milled and calcinated in a rotary kiln at about 1,075 – 1,150 [°C] (Schmidt, 2017). In this step, the α-spodumene is transformed into β-spodumene, which is soluble in hot acids, such as sulfuric acid (H_2SO_4). In the next step, the β-spodumene gets mixed with hot H_2SO_4 and afterwards diluted with water. Due to that, lithium sulfate is dissolved (Schmidt, 2017). Afterwards the solution is mixed with calcium carbonate, which enables the removal of impurities such as iron and aluminum. After the following filtration step, sodium carbonate (Na_2CO_3) and calcium oxide are added to the mixture to get rid of impurities such as calcium and manganese (Schmidt, 2017). Afterward, the solution gets neutralized with H_2SO_4, and the concentration of lithium sulfate (Li_2SO_4) is increased. In the final step, the new mixture is heated to 100 [°C] and Na_2CO_3 is added once again. This causes the dissolution of lithium carbonate (Li_2CO_3), which has a purity degree of 99.3 [%] (Schmidt, 2017). This process is not suitable if the concentrate is needed for the battery industry. The battery industry needs a degree of purity of 99.5 [%], which can be achieved through ion exchange (Schmidt, 2017). To get a better overview of the Acid-Roast-Process, the flow chart presented in Figure 2 is a helpful visualization.

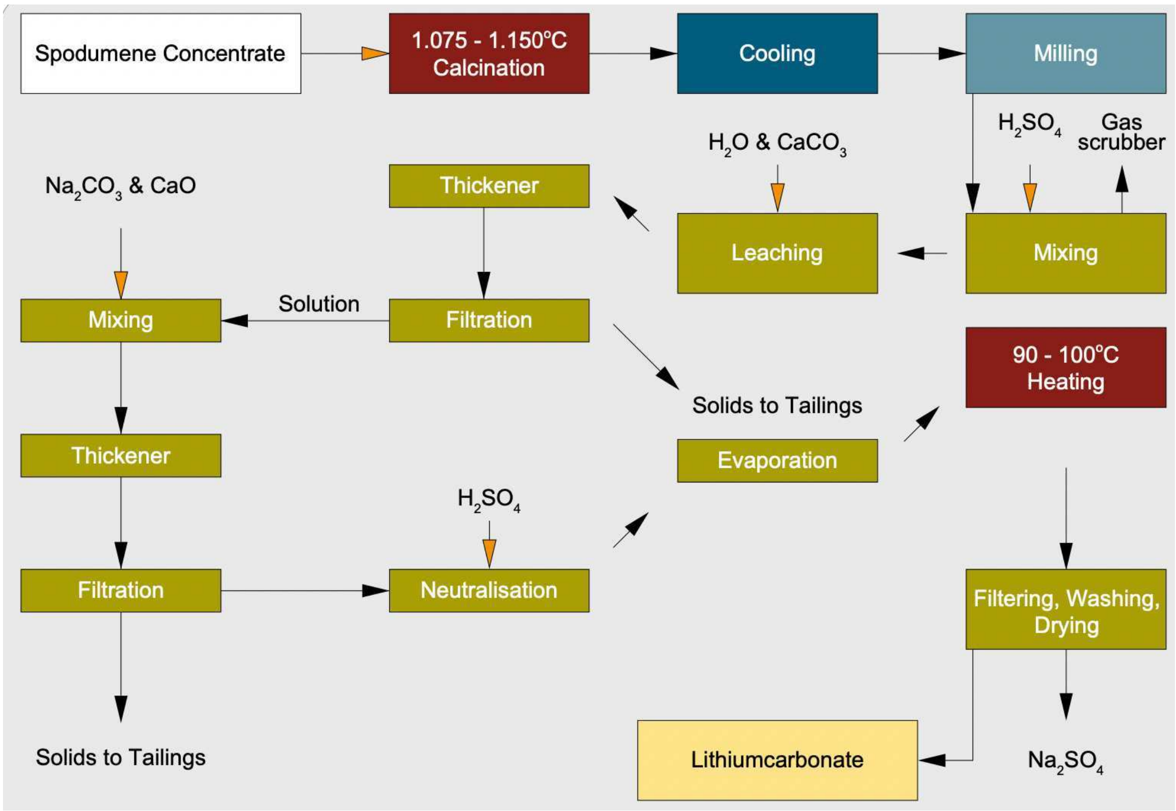


Figure 2: Acid-Roast-Process to produce lithium carbonate (Schmidt, 2017)

Besides the Acid-Roast-Process, there are new approaches for the direct extraction of lithium hydroxide (LiOH) out of spodumene without the process of Li_2CO_3 production. The Nemaska Lithium company for example wants to use a process in which a combination of the Acid-Roast-Process, ion exchange and membrane electrolysis enable the production of a LiOH-solution out of which LiOH-monohydrate ($LiOH \bullet H_2O$) or Li_2CO_3 is produced. In this process, there is no need for Na_2CO_3, and no Na_2SO_4 dissolution occurs (Schmidt, 2017).

Another way to produce lithium concentrates is the Eli-Process invented by the two companies Neometals and Minerals Resources, in which $LiOH \bullet H_2O$ is directly produced out of spodumene concentrate. For this purpose, the α-spodumene is first transformed into β-spodumene, like in the Acid-Roast-Process. It is then mixed with hydrochloric acid (HCl) resulting in a lithium chloride (LiCl) solution. After the removal of impurities, such as iron and aluminum, ion exchange and membrane electrolysis take place. The result of these processes is a LiOH solution, out of which $LiOH \bullet H_2O$ or Li_2CO_3 can be produced (Schmidt, 2017).

All these mentioned processes rely on the transformation from α-spodumene into β-spodumene followed by the use of diverse acids to create a product with a high degree of purity. These steps make every processing of Spodumene very expensive, as they are very energy intensive and therefore cost-driving.

2.2.2 Lithium brines

Lithium brines provide a huge amount of current lithium raw materials to produce different lithium concentrates, that are crucial for the European economy. Lithium brine reservoirs are located beneath salt flats, so-called salars. Most of these salars are in South America – particularly Chile and Argentina – and in China („What is lithium extraction“, 2018).

The process of lithium brine recovery is not very complex but can last very long. Drilling needs to be done to access underground brine deposits so that the brine can be pumped to the surface and filled into evaporation ponds. In these ponds, water evaporates over months or even years and the solid brine material remains („What is lithium extraction“, 2018). The goal of the evaporation process is to increase the concentration of lithium in the brine up to 6 [%] and to get rid of unwanted contents such as carbonates or sulfates due to crystallization (Schmidt, 2017). The amount of such impurities is the main parameter for the technical effort needed to achieve the purity of the wanted lithium product. Hence, these impurities are also one of the main factors which drive production costs (Schmidt, 2017).

2.2.2.1 Processing of lithium brines

The Rockwood Lithium company which operates at the Salar de Atacama deposit applies a processing procedure that is representative of most companies that extract and process lithium brines. In the Salar de Atacama mine, the initial lithium content is about 0.15 [%] (Schmidt, 2017). Due to water evaporation in the ponds, the concentration of the actual lithium content can be increased up to 6 [%], which is the cut-off-grade for further, economic processing. This process step has a huge benefit, as the geographical location of the Salar de Atacama enables the use of solar energy for the evaporation process (Schmidt, 2017). On the other hand, this process can take a very long time of up to 18 months. Another disadvantage of this process is that less than 60 [%] of the lithium that was originally contained in the brine can be recovered (Schmidt, 2017). In a row of consecutive evaporation ponds, sulfates, halides, potasha nd magnesium salts are dissolute. During this process, the brine gets pumped from pond to pond and the dissolute material gets filtered and deposited (Schmidt, 2017). As there are some materials that still can contain lithium, such as bischofite ($MgCl \bullet 6H_2O$), they get processed again before finally being deposited (Schmidt, 2017).

The recovered and concentrated lithium is then processed further. In the next processing step, boron is removed via the so-called solvent-extraction, as it would lead to impurities in the final products (Schmidt, 2017). The brine gets regulated to a pH value of two by using

HCl to achieve this processing goal. Afterward, it is mixed in a 1:4 ratio with a solution that consists of kerosine and a primary alcohol. After this procedure, the brine is mixed with CaO to get rid of residual magnesium and sulfates. The adding of Na_2CO_3 helps to get rid of magnesium and calcium residuals. After that, the brine gets heated and mixed with Na_2CO_3 again, where Li_2CO_3 is dissolved (Schmidt, 2017). After a washing and drying process, the final product is ready to be sold on the world's raw material markets. However, as the processing water still has contents of lithium in it, it gets re-fed to the whole processing circle. Due to these processing steps, the lithium concentrate can reach a so-called battery grade, which has a purity of 99.5 [%] (Schmidt, 2017). A complete list of all processing steps can be seen in the flow chart, which is presented in Figure 3.

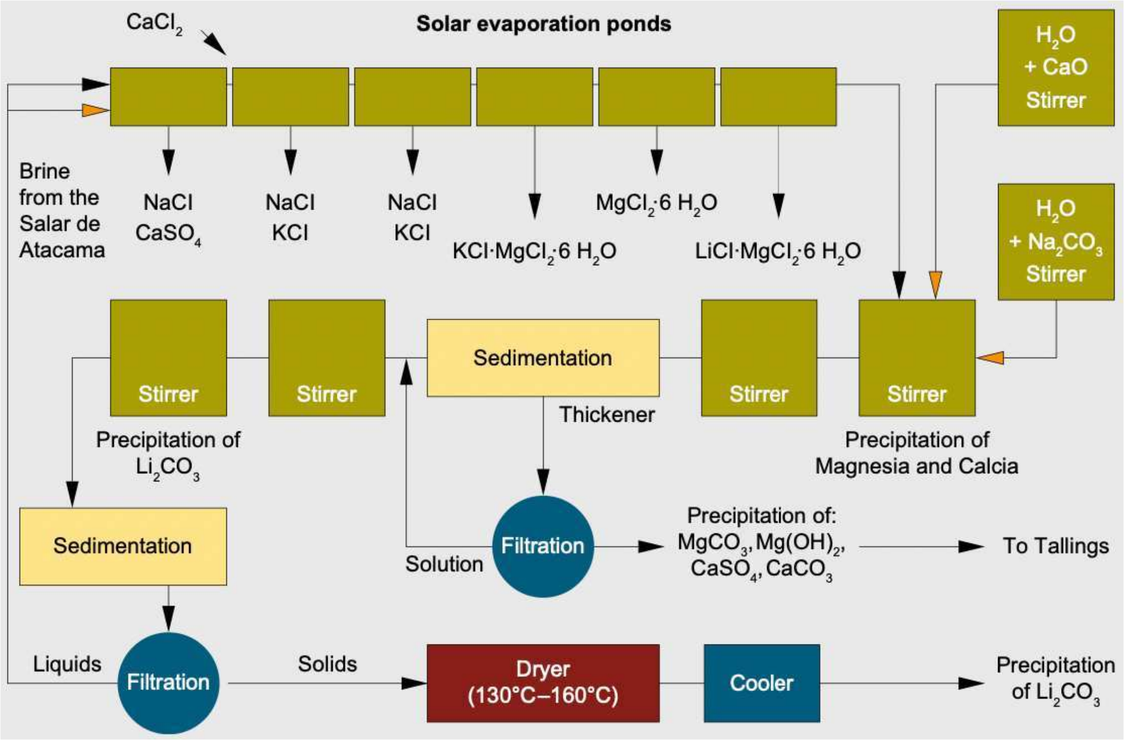


Figure 3: Processing of lithium brines of the Rockwood Lithium company (Schmidt, 2017)

2.3 Lithium recycling

As the world's demand for lithium increases significantly, recycling becomes more and more important. As suggested in "DERA Rohstoffrisikobewertung – lithium 2030 – Update", the demand for lithium will increase from 74,183 [t] in 2020 to approximately 316,307 [t] in 2030 (Schmidt, 2022), which is an increase of more than four times within ten years. This growth in total lithium demand is represented in a compound annual growth rate (CAGR) of 15.6-22.4 [%] per year (Schmidt, 2022). The highest demand growth rate until 2030 is predicted for the production of Lithium-Ion-Batteries (LIB), which will be between 18.9 and 26.5 [%] CAGR. Glass and ceramics industries and the use for lubricating grease, on the other hand, show a considerably lower CAGR of 3.9 [%], each (Schmidt, 2022).

These figures as well as further considerations on lithium use (provided in chapter 2.5), show the importance of proper lithium recycling to provide the much-needed raw material to the European industry in an adequate amount. Additionally, ecology plays a huge role in lithium recycling as the landfilling of LIB represents an environmental threat.

2.3.1 Recycling of LIBs

As most lithium is used to produce LIB, namely 65 [%] of the world's production (Gellenbeck, 2021), this thesis also focuses on its recycling.

Currently, many different processing routes exist for the recycling of LIB. Process steps such as disassembly, mechanical crushing and separation, thermal treatment and pyro- or hydrometallurgical processing, can be combined in many ways (Neef, et al., 2021). Each of the above-mentioned processing steps is described shortly in the following sections to get an idea of what the assembly of these steps could look like.

2.3.1.1 Disassembly process

Considering the recycling of LIB used in cars, for example the disassembly process is always the first step in every common processing option (Neef, et al., 2021). The disassembly can be done manually or automatically; however, currently it is done manually, as the number of recyclable battery packs is still very small (Neef, et al., 2021). Additionally, the modular construction of most batteries makes an automated recycling process difficult and uneconomic. As the number of recyclable batteries is increasing, manual disassembly is going to be impossible in the long run. Due to the need for automated disassembly plants, many of them are in the pilot stage. Processing steps in these plants contain scanning of battery packs, a de-loading step, removal of the cover, removal of electronic elements, cooling elements, isolation and many more until the final processing of the battery cell. As all of these steps can pose high safety risks, careful disassembly is crucial for risk minimization (Neef, et al., 2021).

2.3.1.2 Mechanical processing

In the mechanical processing step, the disassembled cells are shredded. Due to the high reactivity of the contained compounds, this step must take place under a protective gas atmosphere, liquid nitrogen, or a water-salt solution to avoid strong exotherm reactions. Additionally, evolving process gases need to be diluted as they are toxic and acid (Neef, et al., 2021).

After the shredding, vacuum distillation of the fast-boiling compounds of the electrolytes, which potentially could be reused, takes place. A drying step is needed to remove the residual electrolyte compounds. Subsequently, the matals and other components contained in the battery are separated in the mechanical processing. Optional thermal treatment of the battery cell can be performed to remove organic compounds (Neef, et al., 2021).

2.3.1.3 Pyrometallurgical processing

During the pyrometallurgical process, battery cells are fed into a shaft kiln. Thereby, the cells pass different temperature zones in which organic compounds evaporate at first and get reused energetically (Neef, et al., 2021). At higher temperatures, metal compounds melt and cobalt-, nickel- and iron-alloys are reduced to pure metals. The aluminum and graphite which remained in the batteries are used as a reducing agent at this stage (Neef, et al., 2021). The pure metals that are produced in this process form alloys are separated in a following hydrometallurgical process. Other metals, like aluminum, manganese and lithium end up in the slag of the pyrometallurgical process. The lithium can be extracted from the slag also hydrometallurgically. Currently, about 40-50 [%] (Neef, et al., 2021) of lithium can be recovered. However, according to experts, this number could be increased to 70-80 [%] in the future (Neef, et al., 2021).

2.3.1.4 Hydrometallurgical processing

This process step follows the mechanical and pyrometallurgical steps to split up the active materials in a proper way (Neef, et al., 2021). Depending on the recycling system, different materials are processed in the hydrometallurgical step. However, to recover lithium out of LIB, this is the last and most important processing step. Due to this, already improved and common hydrometallurgical processes are described in this chapter.

2.3.1.4.1 Recupyl/TES-AMM process

The TES-AMM hydrometallurgical treatment starts with the leaching of undersized particles from mechanical processing performed in the Recupyl step (Gellenbeck, 2021). Graphite is filtered and does not diffuse into the solution. The chemicals used for the leaching process are not published, but as Na_2SO_4 is a by-product of this process, it is assumable that H_2SO_4 is used as a chemical (Gellenbeck, 2021). However, after the filtration of graphite, cobalt is filtrated in the next step. This happens because of an increase of the pH-value to 7-8, using NaOH, for example to receive cobalt hydroxide ($Co(OH)_2$) as a final product. The last step is the dissolution and filtration of lithium due to the adding of Na_2CO_3. This addition leads to a reaction of the solution and Li_2CO_3 dissolves with a purity higher than 99%. Because of that high grade of purity, it can be reused in LIB production (Gellenbeck, 2021).

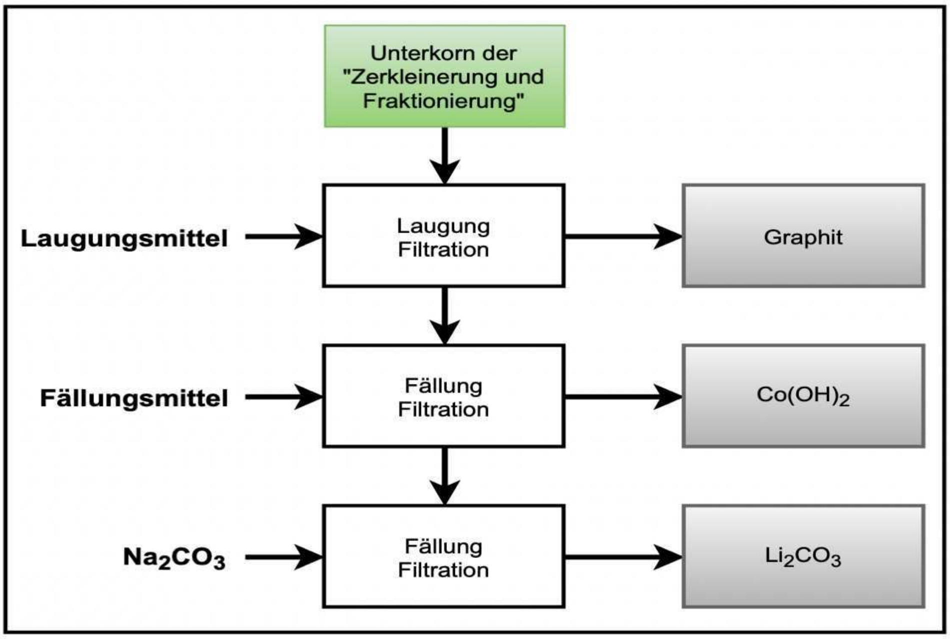


Figure 4: Hydrometallurgical treatment "TES-AMM" (translation see chapter 9) **(Gellenbeck, 2021)**

2.3.1.4.2 Retriev process

In the Retriev process, the material processed in a watery solution is put into a mixing tank together with water. The pH value is held over ten by adding LiOH to avoid the development of hydrogen sulfide gas (H_2S). Additionally, the LiOH avoids contamination of the lithium products that have already been recycled (Gellenbeck, 2021). The material which is in the mixing tank is pressed through a filter press. The remaining filter cake has a cobalt content of about 35 [mass-%] (Gellenbeck, 2021), which can be sold directly to the metal industry, or processed further into high-quality cobalt whereas the filtration liquid already consists of lithium (Gellenbeck, 2021). This liquid is used in the shredding process or is filled in another mixing tank, in which Li_2CO_3 with a purity of more than 99 [%] precipitates due to the addition and further chemical reaction with Na_2CO_3 (Gellenbeck, 2021). These process steps can be seen in the following flowchart.

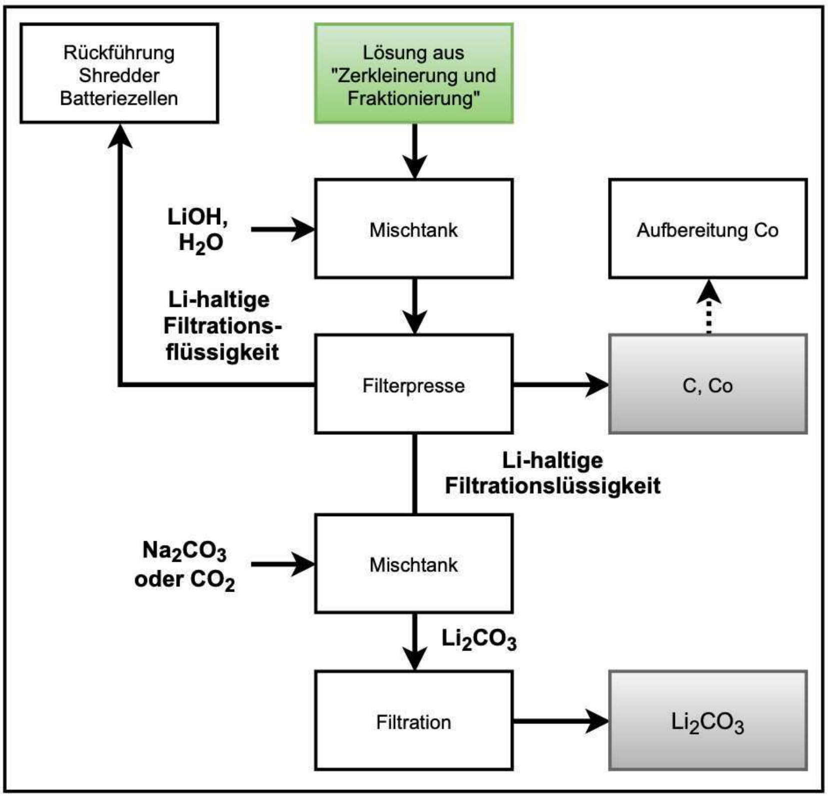


Figure 5: Flow chart Retriev process (translation see chapter 9) **(Gellenbeck, 2021)**

2.3.1.4.3 LithoRec process

In the LithoRec process, the shredded material undergoes a leaching step in an H_2SO_4 and water mixture as a first step (Gellenbeck, 2021). In this process step, hydrogen fluoride, which is highly toxic, is detached. This ensures safer working environment. In the second step, graphite is filtered and copper is precipitated using NaHS, which reacts with the containing copper to CuS or Fe, which cements metallic copper (Gellenbeck, 2021).
Following this step, iron and aluminum contaminations are precipitated due to oxidation. As an oxidant, H_2O_2 beeing used, and the process takes place under a pH value of 4.3- 8.7 (Gellenbeck, 2021). Further, nickel and cobalt are detached as $NiSO_4$ and $CoSO_4$ because of solvent extraction, which consists of many process steps (Gellenbeck, 2021). The residual manganese can be recycled and precipitated by adding Na_2CO_3 or NaOH, whereby $MnCo_3$ or $Mn(OH)_2$ result as a reaction product (Gellenbeck, 2021). In the final step, the precipitation of lithium is achieved by the addition of Na_3PO_4 or Na_2CO_3, which leads to a reaction product of either Li_2PO_4 or Li_2CO_3 (Gellenbeck, 2021). The whole process is visualized in the following flowchart.

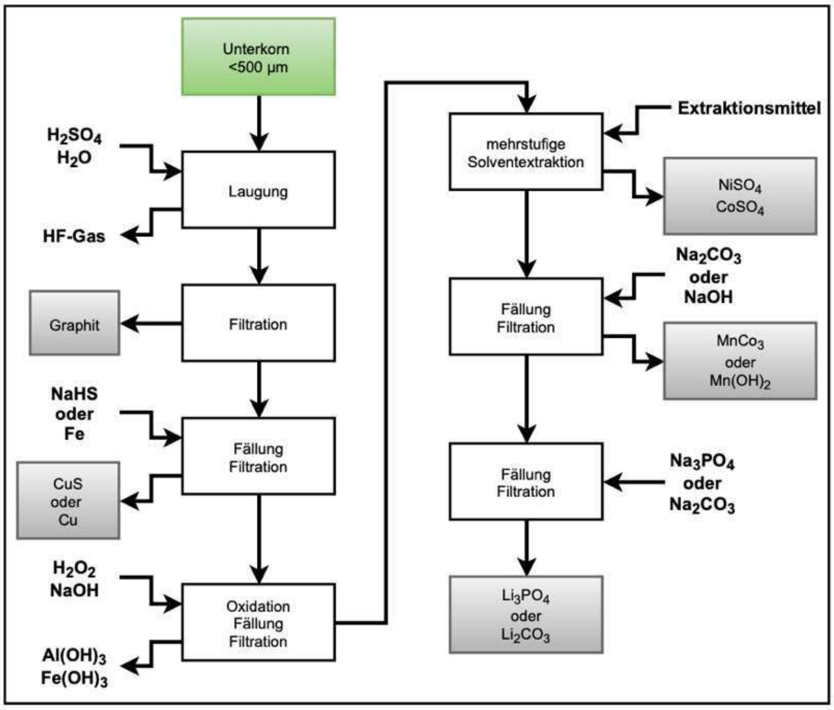


Figure 6: LithoRec recycling process (translation see chapter 9) **(Gellenbeck, 2021)**

2.4 Potential of the primary and secondary lithium extraction

As described above, there are many ways to produce lithium, either using primary extraction or through many different recycling processes. However, in Europe lithium is only mined in small amounts. In this chapter, the mass flows of lithium in and out of Europe are examined. Additionally, problems and reasons why possible deposits in Europe are not mined are discussed and elaborated. Furthermore, three examples that embody the most current problems in the lithium mining industry are described in detail.

2.4.1 Mass flow of lithium-containing raw materials in Europe

According to the RE-SOURCING report “State of Play and Roadmap Concepts: Mobility Sector”, the global primary lithium production was 94,900 [t] (Betz, et al., 2021) in 2018, but according to the World Mining Data, it was 185,850 [t] (Reichl, Schatz, 2022). This difference is due to the fact that the World Mining Data counts lithium production in Li_2O content and not in pure lithium. However, the World Mining Data is used for further numbers, as it provides a good overview on the distribution of raw material production. Using World

Mining Data shows that the global lithium production in 2020 was 185,850 [t] (Reichl, Schatz, 2022), measured as Li_2O content.

Nevertheless, according to RE-SOURCING, the EU`s import of lithium is very high. It is about 20,000 [t] per year (Betz, et al., 2021). The total amount of pure lithium produced worldwide is 94,900 [t] and 20,000 [t] are imported in the EU, which equals about 21 [%] of the worldwide produced lithium (Betz, et al., 2021). Furthermore, due to the annual primary lithium production in the EU of about 280 [t LiO_2] (Reichl, Schatz, 2022), mainly mined in Portugal, it is clear to see that the imported amount of lithium into the EU is enormous. Self-supply is about 1.4 [%] compared to the amount of lithium imported. Considering these numbers, it becomes clear why the recycling of lithium out of LIB gets more and more important, as they are responsible for 57 [%]of the lithium demand (Betz, et al., 2021). However, to feed the European lithium hunger without being dependent on other countries, the mining of primary lithium sources should be increased, if possible.

2.4.2 Mining potential and problems in Europe

The mining of lithium is often connected to various problems. Is the amount of raw material economically mineable? What is the legal situation to gain licenses for the overall production process from mining to final product? Is the social license to mine given? These are a few problems that can occur during the planning of a mining project. However, the potential of lithium mining in Europe is given and should be taken into serious consideration in order to reduce the dependency on non-European countries when it comes to lithium production.

2.4.2.1 Lithium project “Weinebene” Austria - Project history and details

In Austria, a lithium deposit can be found in the region of Carinthia, in the so-called “Weinebene” mountains. In 1981, an Austrian governmental company called Minrex discovered the occurrence of lithium raw materials in this area (European Lithium Ltd., n.d.). Minrex completed a huge process of exploration work consisting of surface geology mapping, 17,000 [m] of diamond drilling and 1,400 [m] of shaft development (European Lithium Ltd., n.d.). In 1988, due to the lower demand for lithium, the Austrian government decided not to develop the project and Minrex was closed. Hence, the project was transferred to Bleiberger Bergwerksunion (BBU), which is a government-owned lead-zinc mining company (European Lithium Ltd., n.d.).

However, in 1991, also BBU was closed by the Austrian government and the project was sold to the private mining compan Kärntner Montanindustrie GmbH (KMI). KMI took care of all the necessary work with the mining authorities, such as mining and exploration licenses (European Lithium Ltd., n.d.).

In 2011 KMI was granted a mining license for the project. Afterwards, Global Strategic Metals (GSM) and Exchange Minerals acquired the project from KMI for 9,7 million [€] plus a 20 [%] value-added tax (VAT) (European Lithium Ltd., n.d.). Furthermore, GSM has spent 1.83 million [€] on exploration and development, which included more drilling, a scoping study, and additionally the extraction of two 500 [t] bulk samples in 2013 (European Lithium Ltd., n.d.). In 2014 GSM de-listed from the ASX and demerged from the project so that European lithium could seek admission to AIM (European Lithium Ltd., n.d.). In 2016 they signed a binding term sheet agreeing to a reverse takeover with Paynes Find Gold Limited and proposed a relisting on ASX (European Lithium Ltd., n.d.).

Project and geological data

In 1985, an exploration programme from the northern side of the “Brandrucken” was undertaken. It included the the development of a decline through the amphibole schist to provide access to pegmatite veins (European Lithium Ltd., n.d.). The European Lithium Ltd. further explains that *“Crosscutting drifts were driven along strike of selected veins to provide access for mapping and sampling and an additional decline was driven to access the veins in the mica schist. In all 1,389 [m] of underground development was mined.”* (European Lithium Ltd., n.d.). Additionally, a drilling campaign of 4,715 [m] to effectively infill the surface drilling to about 50 [m] in the eastern part of zone 1 was conducted (European Lithium Ltd., n.d.), which is visualized in Figure 7.

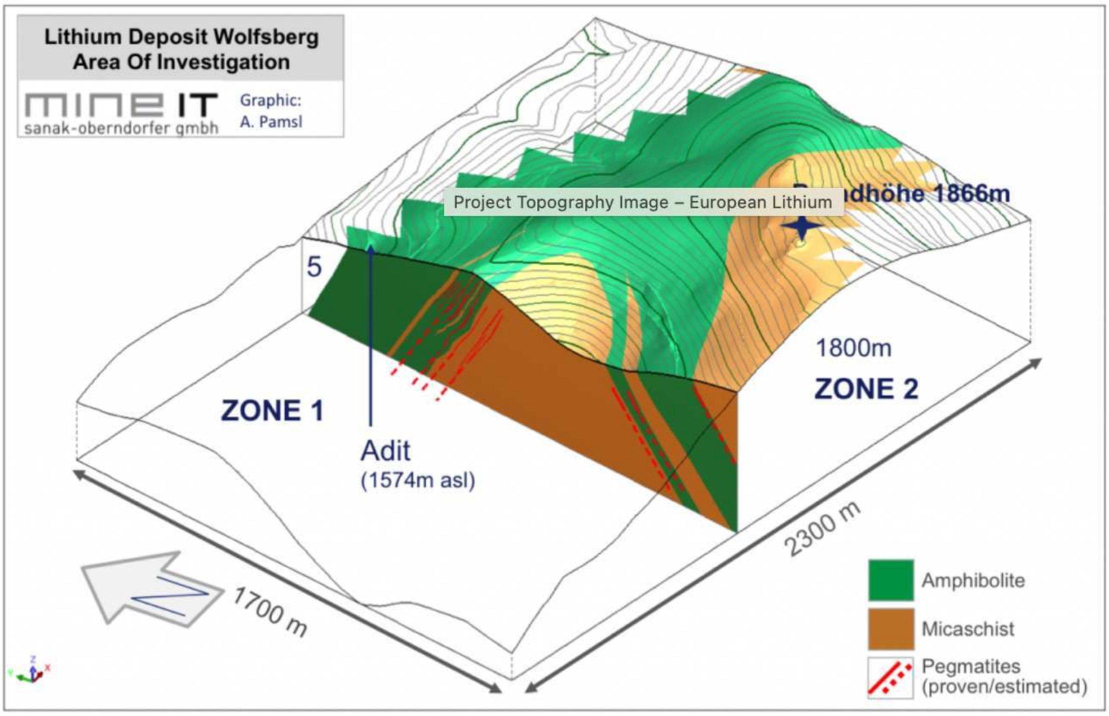


Figure 7: Topography of the "Lithium Deposit Wolfsberg" (European Lithium Ltd., n.d.)

"Following the acquisition of the Wolfsberg project, GSM undertook exploration drilling in 2012 on the southern limb of the anticline which confirmed the structural interpretation and presence of lithium bearing pegmatite veins." (European Lithium Ltd., n.d.) In 2013, mining operations were undertaken to validate the mining license and further to collect about 500 [t] of bulk samples for metallurgical testing. The drilling data of "Minrex" was used to develop a three dimensional resource model for mine planning (European Lithium Ltd., n.d.).

The deposit is split into two zones:

Zone 1

> *The northern limb of an anticline was drilled by Minerex down dip to a maximum depth of 450m and mapped over a distance of 1500m. Lithium-bearing pegmatite veins up to 5.5m wide intersected, and ore body remains open along strike to the west and down dip.* (European Lithium Ltd., n.d.).

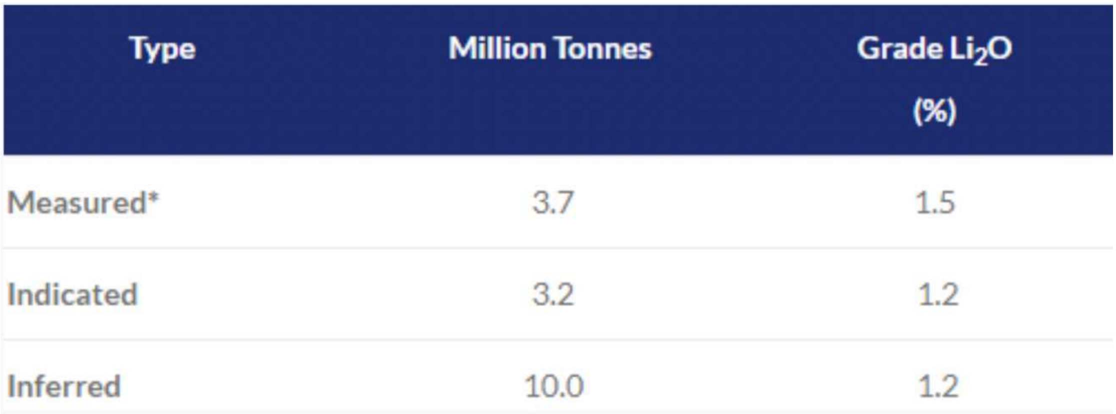
"Minrex" mined about 1,389 [m] of crosscuts, drives and other infrastructures and completed about 16,727 [m] of drilling (European Lithium Ltd., n.d.).

Zone 2

“The exploration target demonstrated to be the southern limb of an anticline, of which the northern limb (Zone 1), was the focus of all exploration by Minerex” (European Lithium Ltd., n.d.) as it is assumed, that this area mirrors the resources of Zone 1 (European Lithium Ltd., n.d.).

> *The resource was declared by previous owners to German and Austrian reporting standards and by GSM to JORC Code (2004). JORC 2004 measured resource at a cut-off grade of 0.75 [%] Li_2O derived from a global measured resource of 4.7 million [t] at 1.2 [%] Li_2O.* (European Lithium Ltd., n.d.)

The results of the measured resources from 2004 are depicted in Figure 8.



Type	Million Tonnes	Grade Li_2O (%)
Measured*	3.7	1.5
Indicated	3.2	1.2
Inferred	10.0	1.2

Figure 8: Resource data JORC 2004 (European Lithium Ltd., n.d.)

After further investigation of the geological properties of the deposit, in 2017 it has been found out that the deposit seems to provide total resources of 10.98 million [t] with a Li_2O – grade of 1 [%] (European Lithium Ltd., n.d.). According to Dietrich Wanke, CEO of ECM lithium Austria GmbH, the feasibility study for the whole project will be finished in 2022 (Zarfl, 2022). Then, up to 11.000 [t] of industrial usable LiOH shall be processed per year. This production rate would last a total mine life of about 18 years, according to Wanke (Zarfl, 2022). However, if allowed by external circumstances the commercial mining process shall start in 2024 (Zarfl, 2022).

Environmental and social discussion

These external circumstances could lead to severe problems concerning the start of commercial mining activity, as there are huge concerns about the environmental influences of the mining activity among the inhabitants in the area around the planned mine.

In 2022, a TV report said that an environmental impact assessment is not needed for the mining project (Auer, 2022). Nevertheless, the mayor of Frantschach demands such an assessment, as it provides full transparency over everything that has to do with the project, especially over environmental emissions such as noise and fine dust (Kakl, 2022). However, until now, there has been no realistic and feasible project presented to the province of Carinthia and the Federal Ministry Republic of Austria Finance, regions (Kakl, 2022).

Resume

By now, over four decades have passed and except for some bulk samples, there has been no commercial mining activity. However, every couple of years, new investors seem to provide money for further exploration of the area. Further, it seems that the so-called “social license to mine” is not given by the population. Finally, one can say that a “European potential” is not given by now according to this mine, as there have always been too many problems of different types, which avoided the commercial mining of lithium ore in this area.

2.4.2.2 Jadar project Serbia - Project history and details

The mineral jadarite is named after the Jadar area, which has been discovered by the Rio Tinto company in 2004 in western Serbia, near the city of Loznica (Rio Tinto, 2022). According to Rio Tinto, the Jadar project is one of the largest greenfield lithium projects in the world. It will produce battery-grade lithium carbonate, as well as borates, which can be used to produce renewable energy equipment such as solar panels and wind turbines (Rio Tinto, 2022).

The whole project includes an underground mine with all the needed infrastructure and equipment as well as a chemical processing plant which guarantees the production of the wanted high grade Li_2CO_3. The first saleable production was expected to start in 2027 (Rio Tinto, 2022); however, there occurred sever problems which will be discussed later. Nevertheless, Rio Tinto is expected to mine 58,000 [t] Li_2CO_3, 160,000 [t] B_2O_3, and up to 255,000 [t] Na_2SO_4 every year, which would make them one of the top ten lithium producers worldwide. Based on these yearly production rates, the mine life is expected to last 40 years while providing 2.3 million [t] of Li_2CO_3 (Rio Tinto, 2022).

Because of all this promising data, Rio Tinto committed 2.4 billion [$] (Schaal, 2022) to the Jadar lithium-borates project. According to Rio Tinto, all relevant approvals, permits and licenses, as well as the engagement with the local communities, the government and the society work out in a very decent way. The final steps that needed to be carried out by 2021 were environmental impact assessment studies, exploitation field licenses and regulatory approvals (Rio Tinto, 2022). However, the project is stuck at a dead end due to massive protests from the inhabitants of the Jadar valley and Rio Tinto is facing new, unexpected challenges.

Environmental and social discussion

Contrary to Rio Tinto, the inhabitants of the Jadar valley and environmentalists see the project as a serious threat for the whole environment in the Jadar valley. They criticize the opaque procedure of the Rio Tinto company in terms of environmental aspects. Environmentalists, NGOs and civilians argue that the Jadar project will contaminate land and water due to the mining and processing activity. According to them, over 15,000 agricultural businesses and all inhabitants in the mining area are affected by these environmental hazards („Proteste gegen Lithium“, 2021). They claim that Rio Tinto has not published key issues about the technologies used for the ore extraction and additionally, it is still unclear how the production will affect the public. According to the CEE Bankwatch Network (as cited in “Proteste gegen Lithium, 2021”), the spatial plans and the environmental assessments give no information about the amount of waste material that is going to be caused by the mining activity. However, the government of Serbia has already declared its support for the project and deemed it as national interest. The processes for granting authorisations have been simplified and also the local infrastructure shall be developed to support the project. Furthermore, media claims that Rio Tinto forces inhabitants to leave the area (as cited in “Proteste gegen Lithium, 2021”); otherwise, they threaten with expropriation. This shall be supported by a legislative decree of the Serbian government. However, this decree was withdrawn after a huge protest from the general public. Since then, Rio Tinto has paused the project („Proteste gegen Lithium“, 2021). Shortly after, the Serbian government has also withdrawn the spatial plans of the project, which is basically the termination of the project, as the most important basis for a mining project does not exist anymore. Rio Tinto announced that they will check the legal basis of the government’s decision. According to Rio Tinto, they already spent over 450 million [$]

for feasibility studies and other investigations for the project („Proteste gegen Lithium“, 2021).

Additionally, Rio Tinto argues that its waste management is focused on a zero-waste policy.

> *The Jadar mine and processing facility will generate two types of waste: rock material from the underground mine – from which jadarite cannot be extracted – and industrial waste produced when processing jadarite. The waste rock from the proposed mine will be placed on a waste rock dump adjacent to the mine shafts. The industrial process waste is a combination of three residue streams produced during different stages of processing.* (Rio Tinto, 2022).

According to Rio Tinto, about 30 [%] of the total waste material will be used as backfill material, the other 70 [%] are then deposited at a landfill site. Rio Tinto claims, that the waste storage will include various modern monitoring systems for air, soil and water to ensure a minimization of potential negative impacts to the environment. Further, Rio Tinto argues that they will take care of a progressively rehabilitation of the land in this area (Rio Tinto, 2022).

Aditionally, Rio Tinto assures that the water management is of highest quality and shall not affect people in the Jadar region.

> *We have done a lot of work to understand the hydrology and to help us understand how we can manage our water use in the best possible way and continue to do so.*
>
> 1. *We are using water from three sources:*
> 2. *Removing and treating water from the underground mine*
> 3. *Collecting surface runoff from the mining and process facilities (e.g. rainfall)*
>
> *Extracting groundwater from alluvium deposited by the Drina river, near Lipnicki Sor. This area has been previously disturbed by gravel extraction and has little potential as a high-quality water source. Water will not be sourced directly from the Drina river bed.*
>
> *The inclusion of a dedicated water management facility on site will result in approximately 70% of the raw water coming from recycled sources (run off) or treated mine water.”* (Rio Tinto, 2022)

Rio Tinto tries to present the project as feasible and environmentally friendly as possible. Nevertheless, government and people seem to not want the mine project started now.

Resume

The Jadar project is a large-scale mining project of the Rio Tinto company. Compared to the “European lithium” project in Austria, it seems to be a project with a very high annual production rate. Mining activities are scheduled to start in 2027. Also, feasibility studies and environmental impact assessments have already been proceeded. However, due to public protests, the Serbian government decided to put the project on hold by now. The Serbian population has concerns in terms of environmental pollution and living standards, which were completely ignored by the government in the early project phases. Nevertheless, a fast rethinking of the government, which is not further commented, put the whole project on hold. Additionally, Serbia is not part of the EU, which could make trading with the EU even harder as Rio Tinto is an Australian company. These issues do not contribute positively to the European lithium mining potential, even though Serbia is located in Europe. On the long run, Serbia would have to become a part of the EU if the EU wants to incorporate the lithium reserves. Nevertheless, if political topics change in a positive way, the Jadar mine could be a very positive commitment towards the lithium independency of Europe.

2.4.2.3 Lithium Iberia project - Project history and hard facts

Lithium Iberia, which is a Spanish mining company, promotes the “Las Navas Lithium Mine” in Canaveral, a small town in the western area of Spain. According to the company, the mine has an approximate lifetime of 30 years of which six years are surface operations and 24 years underground operations („The Carneval Lithium Mine“, 2022). According to current forecasts, the mining will start in 2025 with an expected average production of 1.2 million [t] per year of lithium-containing ore and more than 30,000 [t] per year of battery-grade LiOH („The Carneval Lithium Mine“, 2022). Additionally, Lithium Iberia has already announced that an investment of more than 340 million [€] has been done and more than 430 direct jobs and 1200 indirect jobs will be generated („The Carneval Lithium Mine“, 2022). Currently, Lithium Iberia seeks to receive an exploitation concession from the “Junta de Extremadura” (the administrative authority of the Extremadura region) before the end of 2022, so they can start the planned extraction by 2025. To obtain the needed concession, Lithium Iberia has also presented a restoration plan, in which they present the restoration works about the whole mine life („The Carneval Lithium Mine“, 2022).

Environmental and social discussion

As with many mining projects, ecological and environmental aspects also slow down this project. The city of Caceres, which is in the region of the mining area, is a UNESCO World Heritage. The government of the city is scared that due to the mining activities and the large plants “next door”, this heritage status could be endangered. They argue that not only nature will be destroyed, but also tourism could be significantly reduced due to large industry plants (Neuroth, 2021). The same argumentation comes from the side of hotel owners. They fear that the start of the lithium extraction will end their businesses, as tourists would just watch into the plants of the mine and not into the beautiful nature anymore (Neuroth, 2021). Not only the concern for the residents private businesses and their survival is a sharp criticism of the mining project, but also the fact that mining consumes a lot of drinking water. According to environmentalists, lithium plants are going to use 13 [l/s] of drinking water just to avoid dust emissions. This would result in a consumption of more than 1 million [l] of drinking water per year. As the Canaveral region is known for its lack of rain in the summer months, people are scared that they will run out of water, which would be a catastrophe not only for them but also for the environment in the area (Neuroth, 2021). Because of these issues, people hope that the regional Extremadura government declares the area in which the mining should take place as a nature conversation area. If that is the case, lithium extraction is not possible anymore and the mines will not be opened (Neuroth, 2021).

Resume

According to the reported geological data, the Canaveral area would be a large provider of lithium within the EU. The production of 30,000 [t] per year of battery-grade LiOH would reduce the dependency of the EU on other lithium producers in a significant way. However, as in all three discussed mining projects, discussions about environmental issues are leading factors in whether a mine can or shall be opened. If the lithium mining in the Canaveral area can proceed, the European potential of lithium production will be very high, as this lithium deposit is the largest known in the EU. However, one has to wait for a final governmental decision about the mining operation.

2.4.3 European potential in the area of lithium mining

The three examples discussed in the previous chapters show that there would be opportunities for large-scale lithium extractions in Europe. It needs to be said that the

European Lithium project seems to bring many problems with it before the mining activity even starts. Since 1985, it has been communicated that there is a lithium deposit in the Weinebene mountain. As the company, which has the mining permission, has always communicated that there are various kinds of problems that hinder the start of mining operations, it is hard to assume when the commercial mining activities finally start to proceed. However, there are some other big, confirmed lithium deposits in Europe, as the examples of Jadar and Canaveral show. These deposits are currently not being mined, as there occurred too many different and for now unresolved things, which prevent the companies from starting their mining activity. In Jadar, protesters are concerned with environmental impacts. Further, the Serbian government changed its course from supporting the project to shutting it down. This prevents the creation of new jobs in a very poor and politically and financially unstable region in Europe, as well as the European independency on the raw material market. Jadar would supply Europe and if Serbia had trading contracts with the EU, the EU would have access to 58,000 [t] of Li_2CO_3 per year, which would account for roughly 31 [%] of the worldwide lithium production in 2020 (Rio Tinto, 2022). As already mentioned, the EU imports roughly 20,000 [t] (Betz, et al., 2021) of lithium per year. If Serbia, which has the status of an EU candidate since 2014, would become a member of the EU, the lithium needs would not only be secured, but the EU could also sell lithium based on the current consumption rate. Nevertheless, as lithium consumption will increase not only in the Europe but worldwide, Serbia could provide itself and the EU in the long run with this deposit, as Rio Tinto claims to be able to mine about 58,000 [t] of Li_2CO_3 every year. The Jadar region could be a massive pillar of Europe's potential and standing in worldwide lithium mining.

Additionally, the Canaveral deposit in Spain with a potential production of roughly 30,000 [t] battery-grade LiOH per year („The Carneval Lithium Mine“, 2022) would provide mining potential in the heart of the EU. Not only would it provide over 1600 jobs in the region, but it would also help the EU to become more independent in the lithium market, as this production rate would represent about 16 [%] of the total world production compared to the total production of 2020. Assuming a lifetime of 30 years („The Carneval Lithium Mine“, 2022), this mine could provide lithium to the EU even in a permanently increasing market.

Considering the discussed projects, there is a large potential for the EU becoming independent in the lithium raw material sector if mining companies can ensure a safe mining environment and no environmental damage to nature and harm to the inhabitants around the large mining areas. If there is a solution for the environmental impact of mining, Europe and further the EU can start their way to become a big independent player in the world's raw material market.

2.4.4 Summary of lithium mining in Europe

Apart from the projects examined in the previous chapters, 2.4.2.1 to 2.4.2.3, there is also further potential for lithium mining in Europe. This section provides a general overview to gain additional insights in the current status of lithium mining in Europe. The “Zinnwald Lithium Project” in the German Erzgebirge, the “Keliber Lithium Project” in the Finnish central Ostrobothnia, and the lithium exploration in Cornwall, England, pursued by “Cornish Lithium Ltd” are just a few further examples. In addition to the already mentioned ongoing projects, Portugal has also known lithium deposits, which carry about 27 million [t] of lithium-containing raw material („Portugal plant landesweiten Abbau“, 2021).

However, the described projects have been chosen due to their mine size and thereby, the ability of long-term lithium supply (Jadar and the Iberia mines would be the largest projects in Europe) and due to the fact that one of them is in the nearby area of the Montanuniversität Leoben, namely the Weinebene mine, which would be a great occasion for further academic investigation if the project would launch and it would open a strong standing for the Austrian raw material market within the EU and further in the whole world.

Nevertheless, the other projects coming up in Europe show more or less potential in the area of lithium mining within the European community, as they are all at least in the exploration phase. However, to analyse every single project in Europe and the EU would exceed the scope of this thesis.

Additionally, the three chosen projects show a large social aspect concerning lithium mining as well, which is currently the largest “contra aspect” in terms of lithium mining in the EU. They embody the concerns, thoughts, and opinions of local communities towards mining within Europe in a very accurate way. People seem to have a great demand for lithium, as the European trend goes towards E-mobility and renewable energy, on the other hand, the “not-in-my-backyard” phenomenon occurs as a contradictory effect when talking about mining and mining infrastructure in the “own” area. However, companies need to find a way to convince local and regional communities of their ideas and wants so that the potential within Europe can also be used and consumed. More transparency, environmental impact assessments, job creation and assurance of the current environmental situation must be provided by the mining companies in the long run to gain trust and acceptance in communities which are the most important partner in the mining industry as they give companies the “social license to mine” which effects not only a company but the whole political and economic situations within a country.

2.4.5 European potential in the area of lithium recycling

As the CAGR for LIBs is going to be between 18.9 and 26.5 [%] (Schmidt, 2022), recycling batteries become more and more important. Not only to protect the environment and to ensure the conservation of resources but also to become more independent of the current big players in the world’s lithium market. It has to be stated that there is basically no data about the recycling of lithium itself, but only of whole battery cells. Therefore, it must be mentioned that only rough assumptions can be made in terms of the total number of recycled lithium. Nevertheless, as the recycling of batteries is the main source of secondary lithium, the two largest recycling projects are discussed in the following chapters.

2.4.5.1 Joint venture project Hydrovolt

Hydrovolt, a joint venture between the Norwegian company Hydro, which is one of the world’s largest aluminium companies, and Northvolt, a battery producer based in Sweden and Germany, started the largest European battery recycling plant in Frederikstad, Norway (Dow, 2022). The recycling facility is able to recycle 12.000 [t] of battery packs per year, which is enough for the entire end-of-life battery market of Norway (Dow, 2022). Currently, Hydrovolt claims that it can recover 95 [%] of the materials used in batteries, including lithium. Furthermore, Northvolt will be able to recycle up to 125,000 [t] of batteries every year, which equals approximately 30 [GWh] of battery production per year („Northvolt produces first“, 2021). According to the company, this will lead to newly produced battery cells containing 50 [%] recycled material by the year of 2030 („Northvolt produces first“, 2021).

2.4.5.2 Sungeel Hitech project in Hungary

The South Korean battery recycling company Sungeel Hitech launched one of the largest battery recycling projects in Hungary, Europe. According to the company, the newly built recycling plant in Hungary can recycle about 10,000 [t] of batteries per year. After investing a total of about 30 million [€] in the Hungarian plant, the Sungeel Hitech companys focus lies on the recycling of EV-batteries. Batteries are disassembled in Hungary and further processed in a hydrometallurgical process in South Korea, where chemicals are recycled and brought back to the battery value chain („Sungeel Hightech opens“, 2021). Even though the recycling of batteries is a very important process in many ways, it is questionable if this project in Hungary is a valuable project for the lithium independency of Europe, as the raw material is going to be processed in South Korea. That means that European lithium is brought to South Korea just to be brought back again.

2.5 Usage of lithium raw materials in European industries

As already discussed in chapter 2.4.1, the largest lithium consumer in the EU and the rest of the world is the battery industry. However, not only the electronic and battery sector are large consumers of lithium raw materials, but also the glass and ceramics industries show a huge demand for lithium. Combined, battery applications and the glass and ceramics industries were responsible for 83.2 [%] (Schmidt, 2022) of the world's lithium consumption, as depicted in Figure 9.

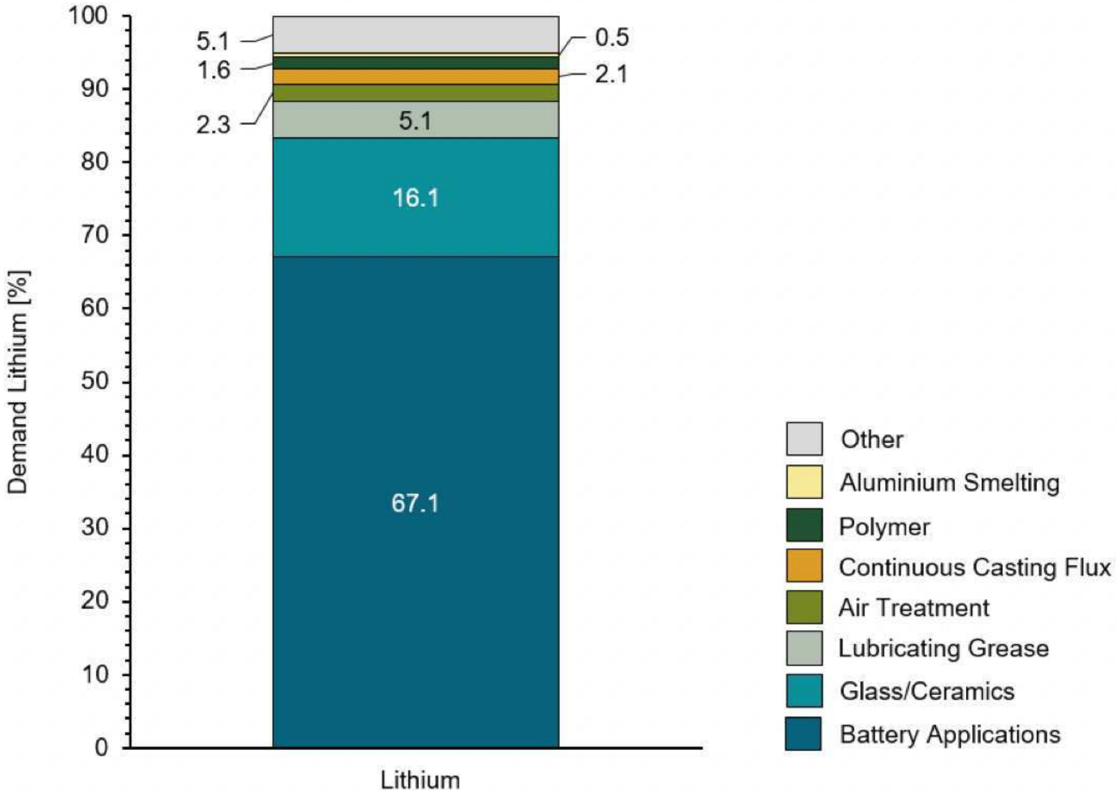


Figure 9: Lithium demand in different industry sectors in 2020 (Schmidt, 2022)

Additionally, the production of lubricating grease is not negligible, as it is the third-largest lithium-consuming industry. Polymer, casting and air treatment industries are also consumers, but they will not be further investigated in this thesis.

2.5.1 Lithium in the battery industry

As the battery industry is the largest consumer of lithium, research on the function, need, and economic value of lithium in different batteries needs to be examined in detail. It is important to understand how the raw material works and if it is really that important for society and the economy.

2.5.1.1 Design and function of a LIB

The basic design of a LIB works for every battery cell in the same way. There are four main components that work in every battery type in the same way. The first component of the battery cell is the cathode. It consists of lithium oxides and variable shares of nickel, manganese and cobalt oxides („Lithium-Ionen-Akkus“, 2022). The anode of the battery always consists of graphite („Lithium-Ionen-Akkus“, 2022).

For the lithium ions to move as charge carriers in the cell, an anhydrous electrolyte is also included in the design of the battery („Lithium-Ionen-Akkus“, 2022).

The fourth main part of a battery cell is the separator. It is installed between the two electrodes, the cathode and anode, in order to avoid short circuits. The separator is made of non-woven fabrics or polymers. It is permeable to lithium ions and can absorb large amounts of other ions („Lithium-Ionen-Akkus“, 2022).

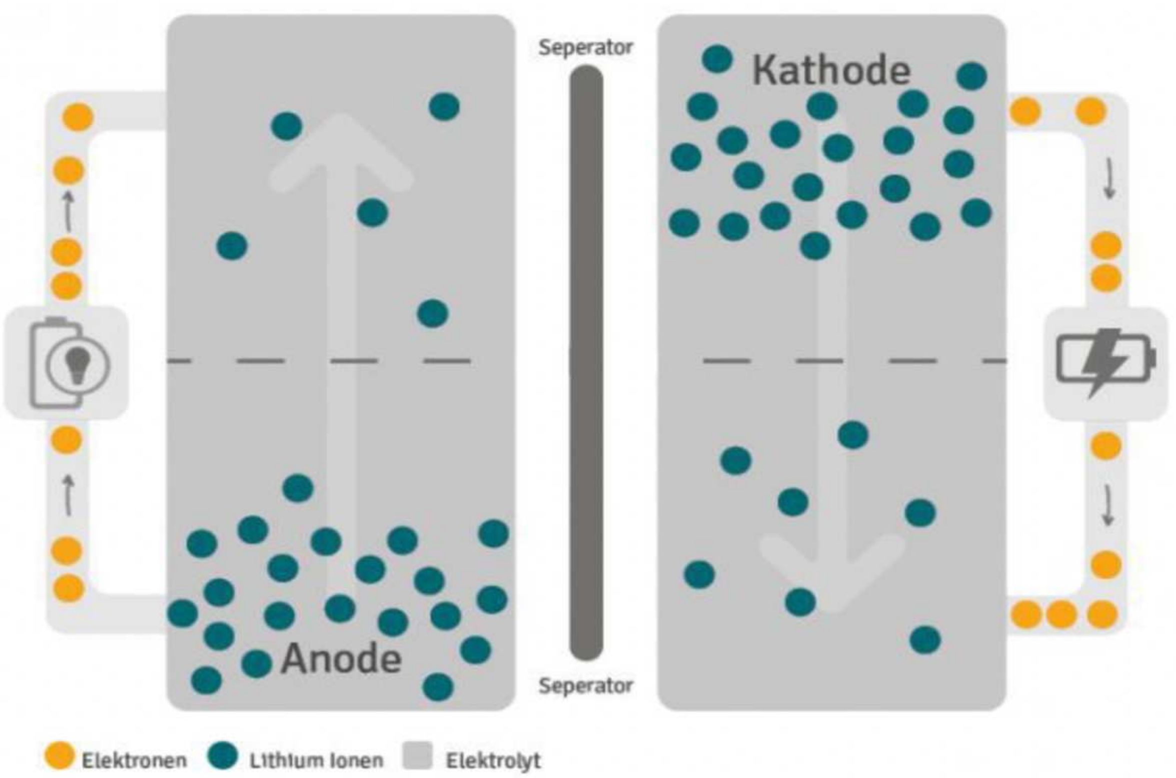


Figure 10: Basic design of a LIB („Lithium-Ionen-Akkus“, 2022)

Once the basic design is explained, the function of a LIB can be understood easily. LIBs function according to a simple principle: Here, the electrical energy in the LIBs is stored by a chemical process and made usable for the drive of pick-up devices. The mode of operation is essentially based on the constant movement of ionized lithium between the electrodes. The lithium-ion flow balances the external current flow during charging and discharging so that the electrodes themselves remain electrically neutral („Lithium-Ionen-Akkus“, 2022).

If the battery is discharged - its stored energy is used by a terminal device - the lithium atoms each emit an electron at the negative electrode. This electron is returned to the positive electrode via the external circuit. In the same step, the same number of lithium ions move from the negative electrode through the electrolyte and the separator to the positive electrode. The electrons are picked up at the positive electrode by strongly ionized so-called transition metal ions. These can be different depending on the type of battery. Unlike lithium ions, they are not mobile („Lithium-Ionen-Akkus“, 2022).

When charging the accumulator cells, the non-ionized lithium atoms move from the positive electrode through the separator back to the negative electrode, where they are intercalated between graphite molecules. The process is also called intercalation and is triggered by charging with constant current until the nominal current is reached. When the end-of-charge voltage is reached, it is maintained while the charging current is decreasing („Lithium-Ionen-Akkus“, 2022).

2.5.1.2 The function of lithium in a LIB

Alkaline batteries provide energy through the electrochemical reaction between manganese dioxide, graphite, and zinc powder. Their main disadvantage is that they cannot be recharged. They belong to the so-called primary batteries, which are produced charged and can only be discharged once („Die sechs wichtigsten Fragen“, 2022).

Conventional lithium metal batteries cannot be recharged either, but LIBs can. They belong to the group of secondary batteries, also called accumulators or batteries for short and can be recharged several times. LIBs also have a higher specific energy (energy per kilo) than other types of accumulators - which predestines them for use in electric cars („Die sechs wichtigsten Fragen“, 2022).

A rechargeable LIB essentially consists of four components, as already mentioned: two electrodes, a liquid electrolyte, and a separator. On the cathode side, a compound of the elements cobalt, nickel and manganese acts as a storage site for the charge carrier lithium. On the anode side, this storage site is made of graphite. Through the electrolyte, the lithium ions are transported from one electrode to the other and vice versa in the "rocking chair principle" („Die sechs wichtigsten Fragen“, 2022).

There are many different LIBs, which differ in size and design, voltage ranges and chemical composition of their components. However, there seems to be no way around the use of lithium as a charge carrier so far. In addition to the high energy density, the long service life and the many possible charging cycles are arguments for the use of LIBs. Other raw materials cannot keep up: Magnesium batteries for example, can only be charged and discharged for 50 cycles, which makes their use uneconomical. They also lag far behind LIBs in terms of charging speed („Die sechs wichtigsten Fragen“, 2022).

So far, no other element offers similar properties for battery applications in electric vehicles as lithium. The raw material is considered to be an unrivaled, irreplaceable charge carrier for the foreseeable future. Nobel Prize winner for chemistry Michal Stanley Wittingham (as cited in “Die sechs wichtigsten fragen”, 2022), who made decisive contributions to research into lithium batteries, expects lithium to remain indispensable for the production of economical, long-lasting batteries for at least another ten years. Unlike cobalt, for example, the share of this raw material in batteries could decline in the next few years. The first manufacturers are already working on developing cobalt-free battery cells („Die sechs wichtigsten Fragen“, 2022).

In the battery of the future, solids could possibly replace the current electrolyte solutions. LIBs would then be history, according to scientists at the Ludwig Maximilian University of Munich (LMU), as cited in “Die sechs wichtigsten Fragen, 2022”. The most prominent candidate as an alternative charge carrier in batteries is sodium. The first sodium-ion batteries could be on the market in just a few years. Other LIB alternatives currently being researched are batteries based on magnesium, calcium or aluminum. However, LIBs are still the charge carriers of the moment - and are likely to keep this roll for a long time to come („Die sechs wichtigsten Fragen“, 2022).

2.5.1.3 Amount of lithium in different battery types

As there are many different battery types, such as so-called AA lithium batteries, which have their typical area of application in household devices, lithium in the batteries of cell phones, or LIBs in the E-mobility sector, one has to consider that there are different amounts of needed lithium raw material for every battery type.

However, most customary batteries have a lithium amount of less than 2 [g] up to 8 [g]. Lithium button cells, which are used in car keys, for example, consist of less than 2 [g] of lithium, as well as common AA batteries. Batteries of sizes C and D have a higher lithium content, which is anywhere between 2 [g] and 8 [g] („Update 2022: Lithium“, 2022).

Cellphone batteries contain approximately 3 [g] of lithium, whereas Laptop batteries have ten times that amount, namely about 30 [g] (Suck, 2017).

Considering electric cars, the amount of lithium contained in LIBs is significantly higher than in normal batteries. However, proportionally, the amount of lithium in such a battery is very low. For example, the typical battery in a Tesla Model S weighs about 600 kilograms, of which lithium accounts for about 10 [kg] of weight - so lithium only accounts for 1.67 [%] of the total weight of the Tesla battery (Mittermeier, 2016). The bottom line is that only 150 grams of lithium are needed per kilowatt hour of battery storage capacity. However, there are other sources that estimate that there are up to 63 [kg] of lithium in a Tesla Model S battery, which weighs, according to the source, only 453 [kg] (Lambert, 2016). Therefore, it is hard to obtain exact information on how much lithium really is built into such a battery. If the exact amount would really be 63 [kg] of lithium in a 453 [kg] battery, this would refer to nearly 14 [%] of the total battery weight.

2.5.1.4 The technical and financial value of lithium in the battery industry

As already mentioned in chapter 2.5.1.2, lithium is the go-to material for the construction of efficient batteries and that will not change in the next couple of years. Additionally, there is no other known element that can provide the same efficiency in battery building as lithium. As already mentioned, magnesium-based batteries work in a technical way, but these are not economical as they survive only 50 loading cycles, whereas lithium batteries last way longer. Therefore, lithium in a LIB is of a very high grade, as it is the main actor for the function and performance of such batteries. Even though the absolute and percentual lithium amount in car batteries changes strongly according to different sources (see chapter 2.5.1.3), it is the center of interest in such a battery. Many other elements, such as cobalt, can be reduced or even substituted in batteries, but that is not the case for lithium at the moment. Therefore, the technical value of lithium is enormous for the electronics sector in the EU, as it is the only element that enables efficient, long-lasting and widely available battery systems.

This is reflected in the lithium price. The average price for battery-grade Li_2CO_3 in the spring of 2022 was 78,000 [$] per metric ton (Probst, 2022). If the Tesla example from chapter 2.5.1.3 is considered, it can be observed that the lithium price is about 780 [$] – 4,914 [$] - depending on the data source- integrated with the car’s battery. Talking about cell phones, which contain about 3 [g] of lithium, the value of lithium in the phone is only 0.23 [$].

Nevertheless, the financial value of lithium compared to the value of its final products is very low. In 2022, the price of the Tesla Model S starts at 106,440 [$] („2022: Tesla Model S“, 2022). This means the value of lithium in a new Tesla S Model is approximately 0.73 [%] – 4.6 [%] of the price of the whole car. Depending on the source of information regarding the lithium content in batteries for this car, the financial value of lithium is either very low or very high. Concluding, it can be said that lithium has to be looked at from multiple perspectieves: On the one hand, the technical value of the product is very high, which means it currently cannot be replaced, as it is essential for the high performance of LIBs; on the other hand, its financial value in the final products is either very low or very high, depending on the data source, as one can see using the tesla example.

2.5.1.5 Substitution possibilities of lithium

Many alternatives for LIBs, such as magnesium batteries are being investigated, but currently they are not as effective or economical as the LIB. In recent years, researchers have made some interesting investigations about the use of sodium-ion-batteries. The two alkali metals, lithium and sodium are chemically very similar. Although sodium does not have the energy density of the comparatively rare lithium, sodium is available everywhere and correspondingly cheaply (Freund, 2020).

However, the performance of sodium-ion batteries lags behind that of LIBs by about 20 years. For decades, research has concentrated solely on the more powerful lithium. In the meantime, there are not only groundbreaking scientific publications but also very promising prototypes: According to a publication from May 2020, a South Korean sodium-ion-battery managed about 500 complete charging cycles before its capacity dropped to 80 [%]. A chemically slightly different battery from a US-Chinese research group managed 450 charging cycles with a similar charging capacity. A Chinese sodium-ion-battery had a slightly lower capacity but still retained 70 [%] of its capacity after 1,200 cycles with 12 minutes of fast charging.

This may not sound like much, but in practice, these batteries would probably survive many more charging cycles because in everyday life, batteries are usually only partially charged and discharged. The complete charging and discharging of a battery in the experiment, on the other hand, puts much more strain on the battery (Freund, 2020). Moreover, sodium-ion technology does not consume scarce resources: the production of cathodes does not require rare lithium salts; instead, simple table salt is sufficient. Powerful anodes can be produced from lignite, wood and other biomass. Cobalt or similar rare resources are not necessary (Freund, 2020).

Fortunately, sodium-ion-batteries are no longer just a theoretical concept. The breakthrough to practical technology seems imminent. The latest research results show that they are already tangible, affordable, and resource-saving alternatives to expensive lithium-ion batteries and that the performance can possibly be increased significantly through multiple intercalations. It will certainly take some time before sodium-ion batteries are technically mature, can be produced in large quantities and can be installed in electric vehicles or mobile phones. But then, a switch in production from lithium to sodium-ion batteries should be largely unproblematic due to the comparatively similar technology (Freund, 2020).

2.5.2 Lithium in the glass and ceramic industry

Lithium is a very important component in the ceramics industry. Lithium-containing glass ceramics are characterized by high mechanical resistance and high resistance to temperature and temperature changes. Lithium also enables the chemical and mechanical resistance of glasses (Lithium, n.d.). According to the “Schott” glass company, lithium is essential for many of their products:

> *Lithium is an essential component in every glass ceramic. Technically, the lithium component is responsible for the zero expansion of the products, which allow them to be used in high temperature ranges without stress rupture. We use these central properties for many of our products: from CERAN® glass-ceramic cooktop panels and ROBAX® fire viewing panels to telescope mirror supports made of ZERODUR® glass-ceramic to PYRAN® fire protection glass and NEXTREMA® for technical applications. Due to the high proportion and high value, the lithium price decisively determines the batch costs of all glass ceramic products.* (Hochdörffer, 2021)

2.5.2.1 Technical function of lithium in the glass industry

In the glass industry, lithium occurs mainly in three types which are: spodumene, petalite and lithium carbonate. Lithium is needed in glass production because of its various properties (Friedl, 2020). One, for example, is that lithium reduces the viscosity of glass melts which shows positive effects on the reduction of gas bubbles within the glass melt, as the gas can evaporate easier due to the high viscosity. Therefore, the glass quality is increased and there are fewer rejected goods produced (Friedl, 2020). Lithium also shows positive effects concerning the productivity of glass furnaces. Additions of 0.1-0.2 [%] increase the productivity of the furnace between 6 [%] and 17 [%] without a reduction of the glass quality. Additionally, the lifetime of a glass furnace is increased as a reduction of melting temperature of the glass mixture occurs because of the lithium in the batch mix (Friedl, 2020).

The exact amount of lithium raw materials beeing used in the glass industry is, unfortunately, very hard to assume, as there exist nearly infinitely many different batch mixtures for every different type of glass.

2.5.2.2 Technical function of lithium in the ceramic industry

In the ceramics industry, lithium has two main functions. It is mainly used to produce glazing or to function as a fluxing agent. Due to the addition of lithium into ceramic batch mixes, the melting point of those batches is reduced and their flux power is increased, which leads to a reduction in burning temperature and time. This leads to a significant improvement in productivity and plant efficiency (Friedl, 2020). Furthermore, lithium reduces the coefficient of thermal expansion of the production in which it is used. One example is enamel, an inorganic glassy mass, which is melted at temperatures above 550 [°C] upon metals. Due to this process, the final product achieves the hardness of glass and the strength of the basic metal (Friedl, 2020). Enamels are used in the production of corrosion-resistant coatings for steel containers, in glazes for tableware to produce white goods and, because of their low coefficient of expansion, in high-voltage porcelain (Friedl, 2020).

The amount of lithium raw material which is used in the ceramics industry is mostly between 0.15 [%] and 2.5 [%] of the ceramic batch mixture. Nevertheless, an accurate calculation of the total lithium amount beeing used in the ceramic industry, is not possible, as the same problems as in glass production occur.

2.5.2.3 Technical function of lithium in glass-ceramics

Lithium is a very important material in the glass-ceramics industry. Glass-ceramics are materials like glass which are produced in a similar way. In the first step, the batch mix is melted, formed and cooled. In the next step, the product is heated up to its nucleation temperature. After a certain holding time at that temperature, a crystallization process starts. Once this process is completed and the product is cooled down again, glass ceramic is produced.

Unlike glass, glass-ceramics own a negative coefficient of thermal expansion, which means that the material is contracting under heat supply. Due to this, crack propagation under quick temperature changes is prevented. This leads to the areas of application such as cooktop panels (Friedl, 2020).

The amount of lithium needed in the glass-ceramic industry is about 3 [%] to 5 [%] of the whole batch mixture.

2.5.2.4 Technical and financial value of lithium in ceramic industry

As it is very hard to find exact compositions of batch mixes for glasses and ceramics, it cannot be said how much lithium is needed for special products in the glass and ceramic industry exactly. Therefore, it is not possible to verify the argumentation of the Schott company, who says that lithium is such a cost driver for glass-ceramics. Accurate batch formulas would help to argue properly concerning this topic.

However, the technical value of lithium in the ceramic industry is high. The so-called CERAN cooktop panels are widely used in European households. Also, ROBAX fire viewing panels are high-quality aesthetic products widely used in private households. Nevertheless, there is no proper data to gain information on how much lithium is needed for every glass type or how much of these special glasses are sold within the EU. However, it can only be assumed that there is a lot of lithium-containing, high-quality glass produced within the EU.

2.5.2.5 Recycling of lithium out of glass ceramics

Even though the total amount of lithium used within the glass-ceramics industry is not as high as in the battery industry, the recycling of it should be considered and pushed forward with more pressure, as it would offer another great possibility of reusing lithium, which ensures a decrease of the needed amount of primary produced raw material. A suitable way to extract lithium out of glass ceramics is a leaching process. According to scientists, the extraction of lithium from glass-ceramic waste has a significant advantage over the recycling process of LIBs since the process is chemically stable (Kim et al., 2021). Additionally, the disassembly of the material as in LIB recycling, is not needed. Furthermore, the phase in which the lithium occurs is Spodumene, the same phase as in the primary raw material extraction (Kim et al., 2021). This results in an amount of four percent of lean Li_2O in the Spodumene, which ensures feasible recycling of the material. The refining of lithium is described as follows (Kim et al., 2021).

> *An acid-free leaching process for lithium extraction from waste lithium aluminosilicate (LAS) glass-ceramics was investigated. Lithium was extracted by a water leaching process after calcination with CaO or a CaO-$CaCl_2$ mixture. Compared to extraction using only CaO calcination, the addition of $CaCl_2$ to CaO can significantly reduce the Si:Ca mixing ratio as well as the thermal treatment temperature.* (Kim et al., 2021)

During these experiments, a magnificent decrease in thermal treatment and leaching time was observed. The crystalline phase which determined the mechanism of lithium extraction was investigated based on thermomechanical calculations and X-ray diffraction analysis. Due to the substitution of the CaO by the $CaCl_2$, the leaching rate of the lithium either decreased or remained constant due to a decrease in the $LiAlO_2$ phase. However, a gradually increase of the lithium leaching rate with an increasing substitution rate of $CaCl_2$ took place, due to an increasing formation of the LiCl phase (Kim et al., 2021).

> *In addition to lithium, calcium and chloride were also observed during the water leaching process. The leaching rate was independent of the thermal treatment and leaching time. Considering conventional lithium purification techniques, a green process for lithium extraction, purification, and recovery from waste LAS glass-ceramics is proposed* as cited in (Kim et al., 2021).

As shown, the recycling processes of lithium out of glass-ceramic products are examined. However, data about large-scale recycling aggregates and their function is not further described and should be investigated to guarantee a suitable, large-scale industrial recycling of such products.

2.5.2.6 Substitution of lithium in glass and ceramic industry

As described in chapters 2.5.2.1 and 2.5.2.2, there are only very low amounts of lithium in different glass and ceramic batch mixtures. Nevertheless, the influence of the raw material on the quality of the final product is very strong. However, as there is way less lithium needed in the glass and ceramics industry, there is no high pressure towards substitution, as the recycling of glass and, thereby, lithium, for example, is already a strong aspect in the glass industry. Anyway, there is no strong indication of lithium substitution in glass and ceramic products now. Furthermore, there can be no information found about the aims of substituting lithium in such glasses and ceramics.

2.5.3 Lithium in the lubricant industry

Another big industry sector, which is rather highly lithium-consuming, is the lubricant industry. Even though there is such a low amount of worldwide produced lithium used in this industry, the raw material is still important in order to achieve specific lubricant properties.

In the lubricant industry, lithium is used mainly as an additive. It is mainly needed in the production of lubricating grease as a thickening agent, where it occurs as so-called lithium soap. Those soaps are salts of long-chain fatty acids. Lithium-based lubricating grease consists of an average of 8 [%] lithium soap. The most important properties of these soaps are the very high drip point of 180 [°C] and very low water solubility, which prevents washing out under humid conditions (Friedl, 2020).

They can be used at temperatures between -55 [°C] and 200 [°C] and are superior to other greases in every respect. These lubricants are used in areas where high speeds and strong mechanical loads occur, such as in the automotive industry (gearboxes, drive shafts), agriculture (machinery), construction vehicles, the steel industry and mining. About 70 % of the lubricants used in technical applications contain lithium or lithium compounds (Friedl, 2020).

2.5.3.1 Recycling of lithium out of lubricants

Currently, there is no research conducted in the area of recycling lithium out of lubricants. As Lubricants consist of an average of 8 [%] of lithium, further developments should be considered, as there could be possibilities to refine a large amount of lithium.

2.5.3.2 Substitution of lithium in lubricants

To date, there is no movement in the area of lithium substitution within lithium-containing lubricants. Nevertheless, the lubricant market offers a wide spectrum of lithium-free lubricants, which could be used as a substitution for lithium-containing ones in many areas of European industry.

3 Cobalt

In this chapter, the properties, mining, and extraction of cobalt out of its primary and secondary raw materials are investigated, such as the environmental impact of those activities. Additionally, the physical and chemical properties of cobalt, which are the reasons for the usage of cobalt in final products, are investigated.

3.1 Cobalt properties

Cobalt is a chemical element with the ordinal number 27 and a molar mass of 58.93 [$g \bullet mol^{-1}$] („Cobalt“, n.d.). Cobalt is a ferromagnetic heavy metal and belongs to the ninth group of the periodic table of elements. The density of cobalt, which has a share of roughly 0.003 [%] of the earth's crust, is 8.9 [$g \bullet cm^{-3}$] („Cobalt“, n.d.). It occurs in two modifications, which are the hexagonal α-cobalt and the cubic face-centered β-cobalt. The specific heat capacity of cobalt is 420 [$J \bullet kg^{-1} \bullet K^{-1}$] („Cobalt“, n.d.). It has a normal potential of -2.13 [V] and a Mohs hardness of 5 [-]. The melting point of cobalt is at 1,495 [°C], and its evaporation point is at 2,927 [°C] („Cobalt“, n.d.).

3.2 Cobalt raw material mining and extraction

According to the mining website “Britannica”, cobalt is mainly found in association with nickel and copper ores (Campbell-Taylor, n.d.). In central African and Russian copper-cobalt ore bodies, the cobalt mainly occurs in the form of cobalt sulfides (carrollite, linnaeite, and siegenite), cobalt oxides (heterogenite and asbolite) and the cobalt carbonate sphaerocobaltite (Campbell-Taylor, n.d.). Cobalt which occurs together with nickel ores in Canada or Australia replaces nickel in many minerals (Campbell-Taylor, n.d.). Further, cobalt occurs in a small amount together with arsenides or pyrite (Campbell-Taylor, n.d.). The main amount of cobalt is mined in the Democratic Republic of Kongo (DRC), namely 70 [%] of the total world production (Betz, et al., 2021). This correlates with the data out of the World Mining Data, which states that the DRC mined 86,591 [t] of a total wold production of 129,110 [t] (Reichl, Schatz, 2022). Large-scale mining is the mining type that provides over 90 [%] of the cobalt mined in the DRC, whilst artisanal and small-scale mining (ASM) provides less than 5 [%] of the cobalt mined in the DRC (Betz, et al., 2021). In past years, this was not the case, as reported:

> *This is unusual and correlated to the low cobalt price and the Corona pandemic. The ratio of ASM compared to LSM in the DRC has been much higher in the past (closer to 25 %). ASM cobalt production has historically been strongly linked to market demand.* (Betz, et al., 2021, p.23)

As indicated by previous market trends, as price increases, the ASM cobalt sector increases to provide the “swing supply” to the world market. Although, the prices for cobalt are currently lower than in 2018 when they had their peak and the ASM shares in the market have contracted, this could change with the market demands (Betz, et al., 2021).

It is expected that stronger regulations of mining practices will slow ASM reactivity to changing market forces. (Betz, et al., 2021) However, ASM is a very important mining system as it provides a safe income for a large number of people in the DRC (Betz, et al., 2021). The strong position of the DRC in the world's cobalt market is shown in Figure 11.

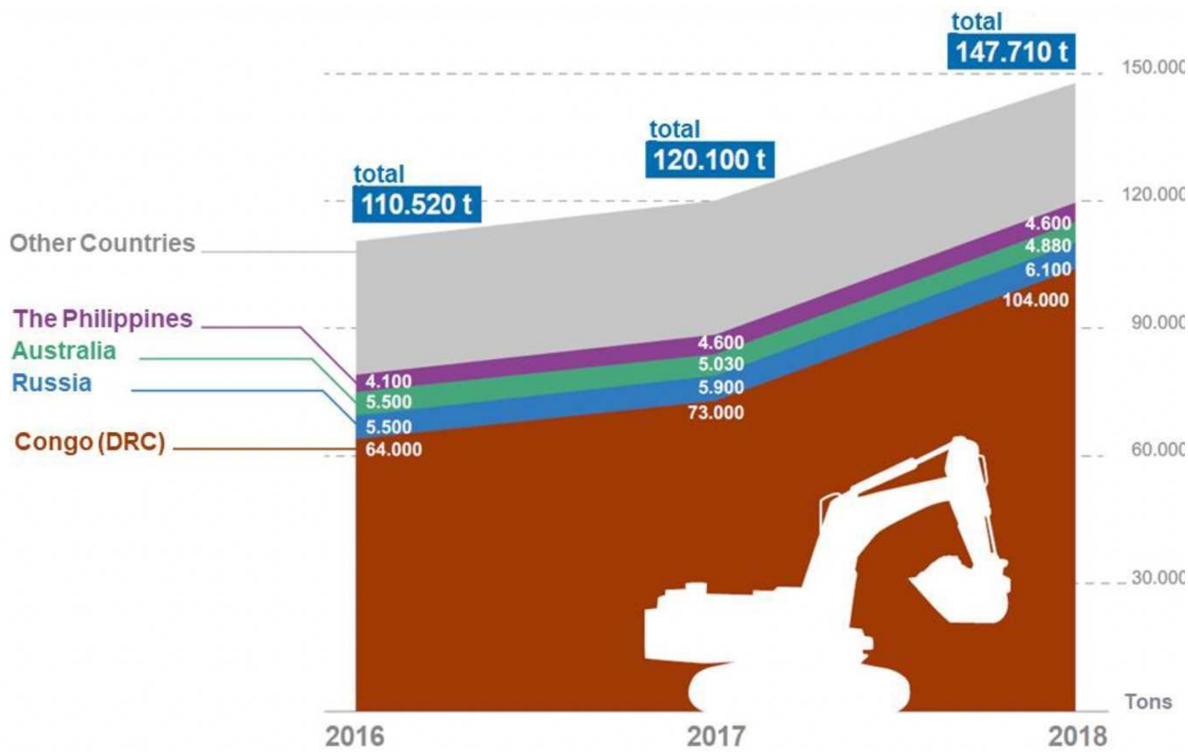


Figure 11: Global primary cobalt production (Betz, et al., 2021)

Whilst the DRC provided 104,000 [t] of cobalt ore to the world’s markets in 2020, the second largest provider, Russia, only provided 6,100 [t]. This shows the strong, dominant position of the DRC, which has a worldwide monopole (Betz, et al., 2021). As already mentioned, cobalt occurs mainly together with copper or nickel ores and is thereby mainly mined as a by- or co-product. However, there exists one modern large-scale mine, namely the Bou Azzer mine in Morocco, which mines cobalt as main product. This mine accounted for roughly 1.4 [%] of the world’s cobalt production in 2017 (Betz, et al., 2021). According to DERA, in 2016 roughly 61 [%] of the worldwide mined cobalt were by-products of copper mining and 37 [%] from nickel mining (Al Barazi, et al., 2018). In 2018, the already mentioned Bou Azzer mine was mining about 2 [%] of lean cobalt ore. As one can see, this value is changing all the time, but it remains roughly in this percental area. However, most industrial mined cobalt is, as mentioned earlier, a by-product of the world's copper and nickel production, and it occurs in contents of 0.1-0.5 [%] in those ores. The final grade of cobalt in the ore concentrates depends on the mineralogical properties of the various ores and reaches between 2.5 and 3 [%] (Al Barazi, et al., 2018). The application rate of cobalt out of sulfidic ores amounts to 80 [%], out of mixed ores 65-70 [%], and out of oxidic ores about 50-55 [%] (Al Barazi, et al., 2018). This leads to a very high loss of cobalt in many ores, which cannot be prevented at the moment.

The extraction type of the diverse ores strongly depends on the orientation and the spatial location of the orebody. In general, copper-containing ores lie flat under the earth's surface and the mining activity starts in an open pit operation which often changes to an underground mining operation due to high depths and changes in ore distribution (Al Barazi, et al., 2018). Cobalt-containing underground nickel and copper ores are mostly hydrothermal or magmatic originated, which leads to the high strength of the ore body. This leads to extraction by drill and blast most of the time (Al Barazi, et al., 2018). The total worldwide cobalt reserves are roughly 7,600,000 [t], according to the "Mineral Commodity Summaries 2022 – cobalt" by the USGS („Cobalt", 2022). Out of these 7,600,000 [t], the DRC holds the largest share, with roughly 3,500,000 [t], followed by Australia with a share of 1,400,000 [t] and Indonesia, with a share of 600,000 [t] („Cobalt", 2022).

3.2.1 Cobalt ore processing

The processing method of cobalt-containing ores mainly depends on the ore type, there are five different methods which are commonly used. Additionally, to the mineralogical properties of the cobalt-containing ore, diverse, ore-specific processing steps have to be taken into account (Al Barazi, et al., 2018).

3.2.1.1 Processing of Congolese cobalt – copper – ores

Due to hydrometallurgical processes, oxidic and non-oxidic minerals are leached, precipitated, or reduced to a pure metallic state. These processing steps are also used for the treatment of cobalt stone and for the cleaning of the cobalt-containing raw materials before they are used in an electrolysis process. During the cleaning of the cobalt-rich leach, solvent extraction and ion exchange processes play an important role (Al Barazi, et al., 2018). However, the most common way of cobalt processing is that cobalt-rich, aqueous raffinate is produced due to a leaching process followed by a separation of solid and liquid phases and a copper extraction into an organic solvent. Metals such as iron and aluminum are precipitated due to an addition of SO_2, fresh air and CaO. Once this has been done, further copper and aluminum rests are once again precipitated using the addition of CaO. Further, cobalt hydroxide precipitation occurs due to the addition of MgO and CaO to the aqueous solution. Once the cobalt occurs in a solid state, it gets filtered and dried until it reaches a moisture content of 15 [%] or it is left at a moisture content of 60 [%] once it is ready to be offered to the raw material markets (Al Barazi, et al., 2018).

A flow chart of the exact processing steps is provided in Figure 12.

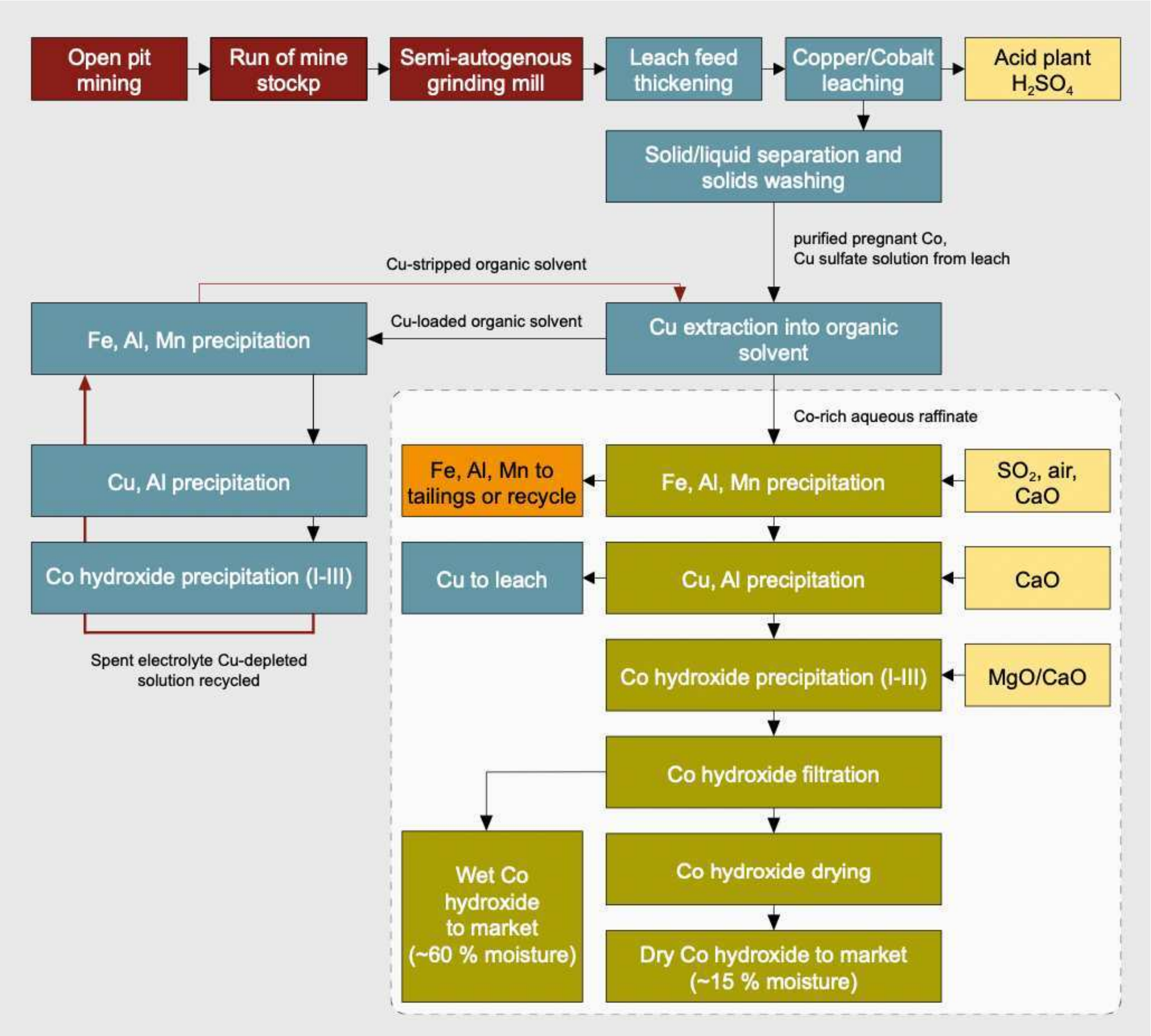


Figure 12: Processing flow chart of Congolese cobalt–copper-ores (Al Barazi, et al., 2018)

3.2.1.2 Processing of Congolese copper sulfides

Congolese flotation concentrates show a typical copper content of 46 [%] and a cobalt content of 0.4 – 2.5 [%] (Al Barazi, et al., 2018). Normally, the copper ores produced using a flotation process undergo a sulfurizing roasting process before they are leached in sulfuric acid. During this process, the containing cobalt undergoes the same processing steps as the copper ore. In the next step, a separation between solid and liquid contents takes place. Thereby, the copper is extracted into an organic solvent. Afterward, other accompanying substances such as iron and aluminum are removed. In the last two steps, the containing copper hydroxide precipitations are redissolved using electrowinning (Al Barazi, et al., 2018). The final product is a high-purity cobalt concentration. The specific process is depicted in a flowchart in Figure 13.

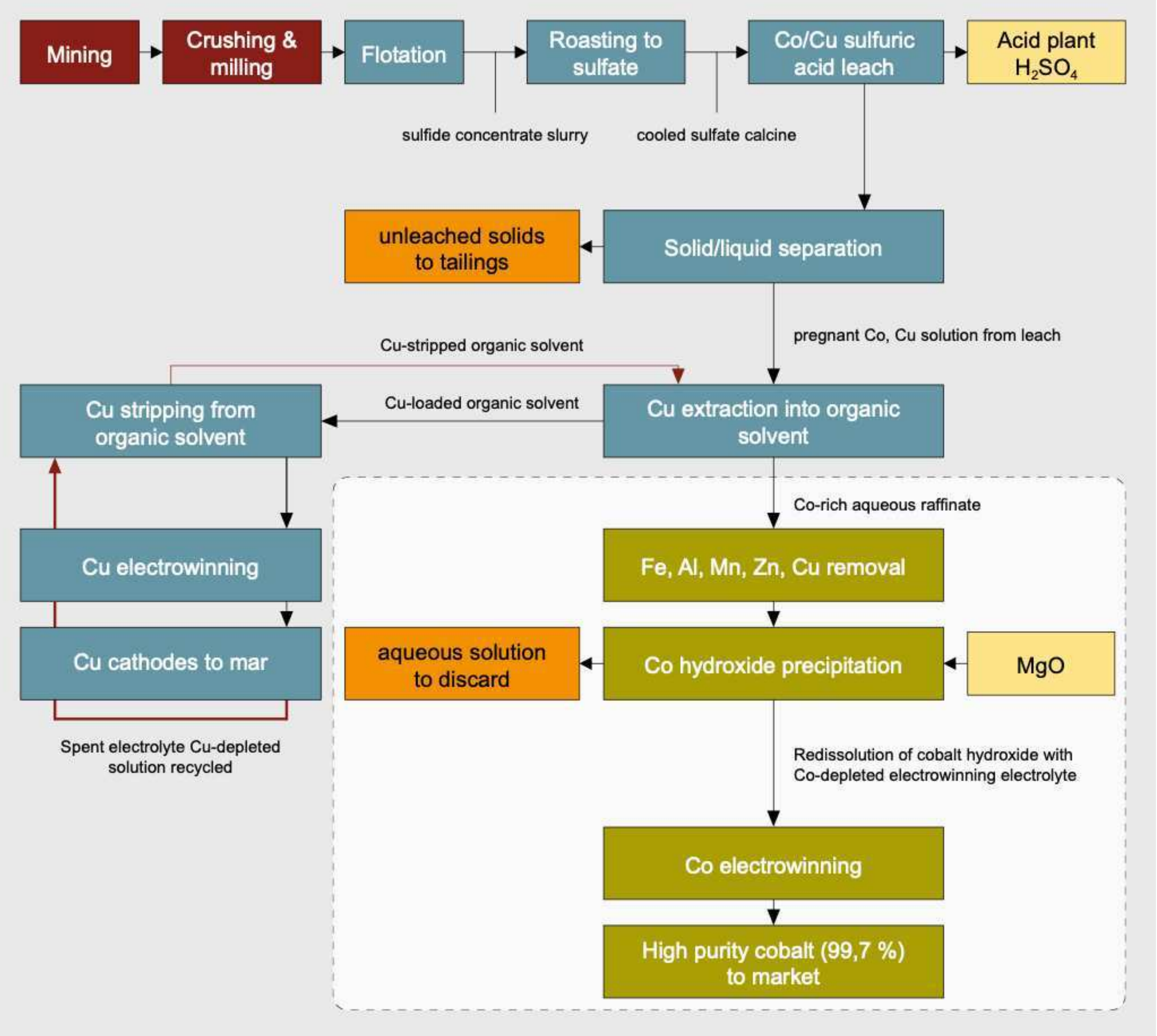


Figure 13: Processing flow chart of Congolese sulfidic cobalt–copper–ores (Al Barazi, et al., 2018)

3.2.1.3 Processing of cobalt-containing lateritic ores

The production of high-concentrate cobalt products out of lateritic, cobalt-containing nickel ores is led by the high-pressure treatment of limonitic ore sludge under the influence of hot H_2SO_4. Out of the thereby produced solution, nickel and cobalt sulfides are precipitated due to the addition of H_2S to the solution (Al Barazi, et al., 2018). The whole processing scheme of lateritic ores can be seen in the flowchart of Figure 14.

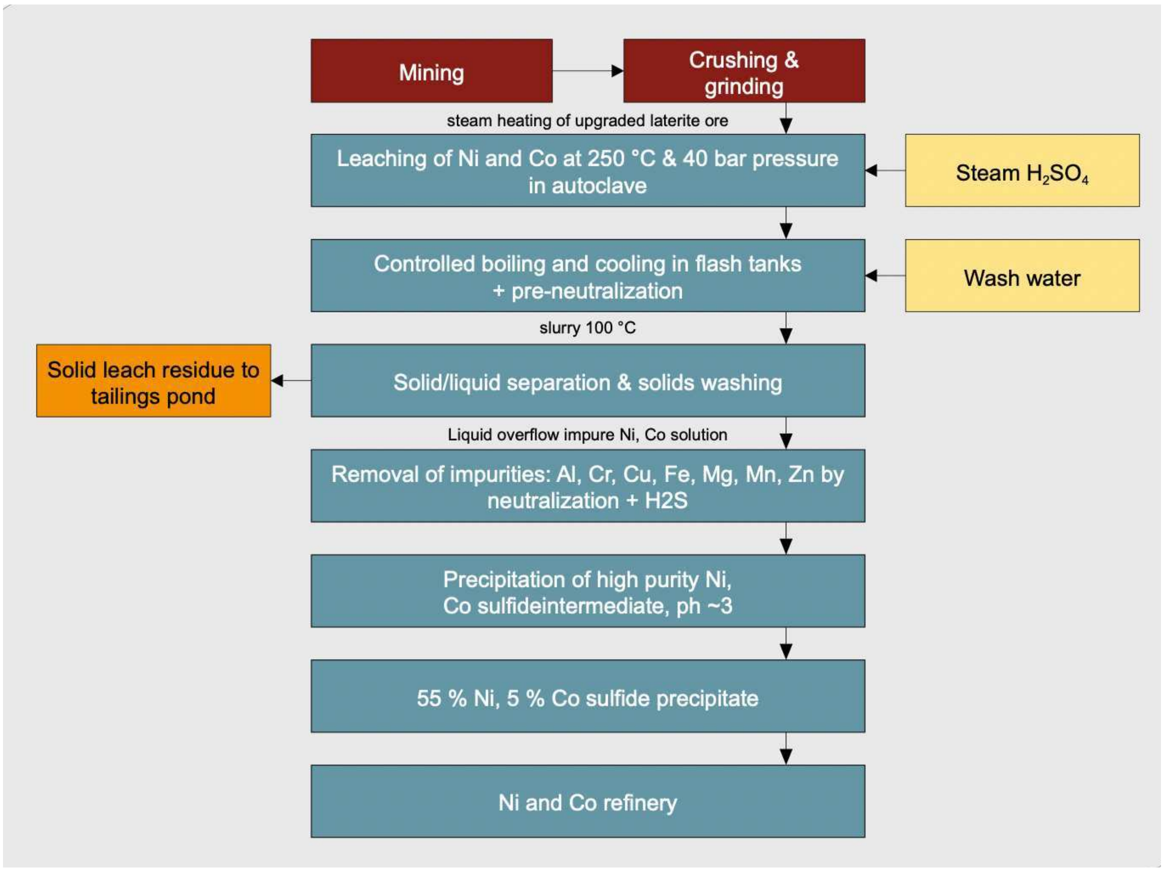


Figure 14: Processing flow chart of cobalt-containing lateritic ores (Al Barazi, et al., 2018)

3.2.1.4 Processing of nickel-sulfide ores

In the processing of nickel–sulfide ores, nickel concentrates are partially roasted in order to be able to subsequently slag the often in these ores containing iron sulfide as an oxide in an electric furnace or in a blow converter (Al Barazi, et al., 2018). The following melting process is conducted in a specific way that the slag produced shows as low nickel content as possible. Nickel and cobalt then accumulate in nickel fines which are cast into anodes.

These anodes are then subjected to reduction electrolysis in a medium of diluted sulfuric acid, whereby nickel of commercial purity is deposited on the cathodes of the electrolysis cells (Al Barazi, et al., 2018). The other components of the anode, such as cobalt, remain in the electrolyte and are recovered in a multi-stage wet chemical process (Al Barazi, et al., 2018).

Another process for the treatment of nickel concentrates involves a levitation melting of the concentrate. The resulting nickel matte is blown into nickel fines in a converter (Al Barazi, et al., 2018). The nickel fines are then ground up and subjected to multi-stage pressure leaching with ammonium sulphate lye with the addition of ammonia (Al Barazi, et al., 2018). A particular advantage of this process is the continuous production of ammonium sulphate, which is sold as mineral fertilizer (Al Barazi, et al., 2018). The reduction of metallic nickel from the ripened leach is carried out with hydrogen under pressure, producing a nickel powder that is sintered and sold as rondelle (Al Barazi, et al., 2018). The cobalt remaining in the leach is produced as sludge during leach purification and must be recovered in subsequent wet chemical processes (Al Barazi, et al., 2018). These sludges, which typically contain 8-10 [%] cobalt, 28-34 [%] nickel, 0.4-0.8 [%] copper and 5–6 [%] zinc are selectively reduced with sulfur dioxide in the first step, with the aim of leaching cobalt and nickel out of the sludges and thus removing the iron and part of the copper remaining in the sludge (Al Barazi, et al., 2018). The lye then contains 14–16 [$g \bullet L^{-1}$] cobalt, 45–65 [$g \bullet L^{-1}$] nickel, 0.4–0.8 [$g \bullet L^{-1}$] copper, and 3–5 [$g \bullet L^{-1}$] Zinc (Al Barazi, et al., 2018). In subsequent purification processes, the cobalt is precipitated from the nickel solution by hypochlorite, producing cobalt hydroxide (Al Barazi, et al., 2018). The purified cobalt hydroxide is calcinated to produce cobalt oxide, which is melted, reduced and cast into cobalt anodes. The cobalt anodes are, in turn, refined into cathode cobalt in an electrolysis process. This produces a tradeable product of high purity with 99.98 [%] cobalt (Al Barazi, et al., 2018). The flowchart, shown in Figure 15, shall help to understand those processes.

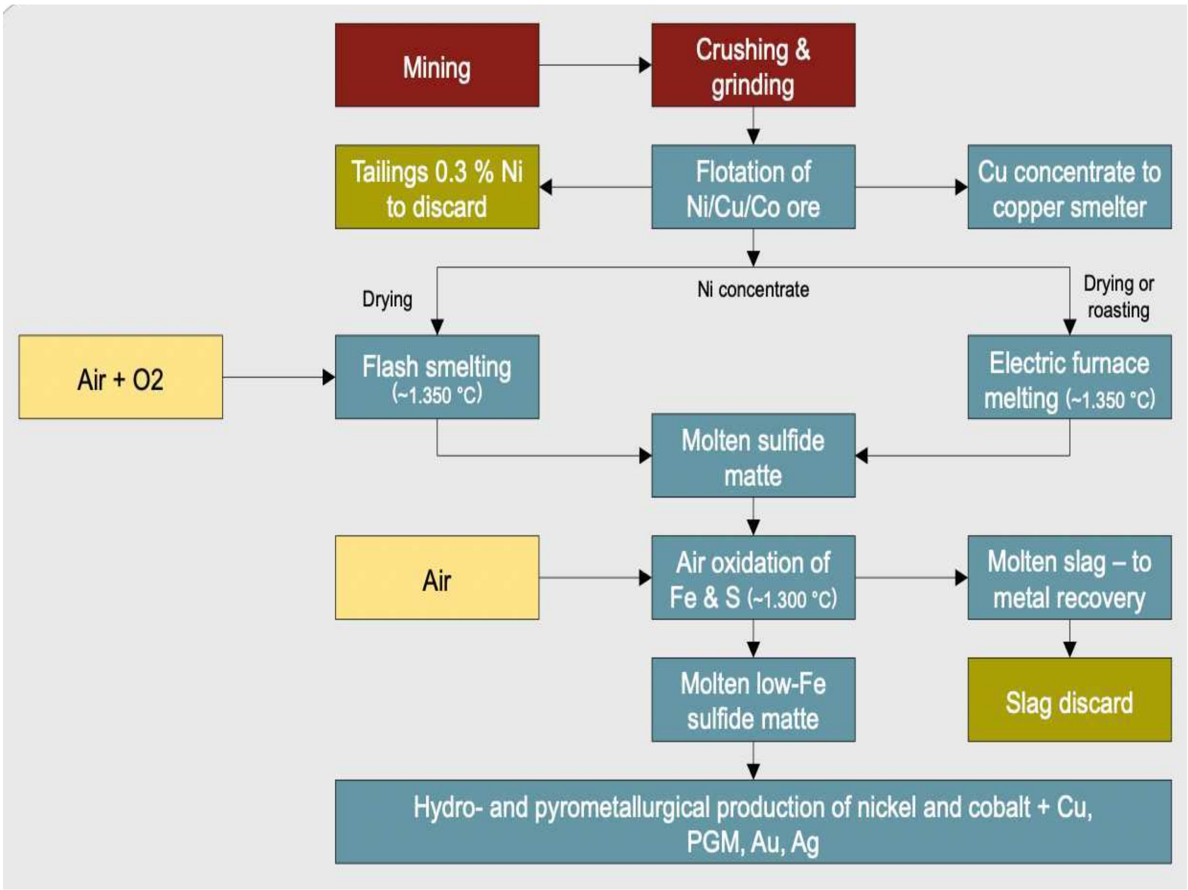


Figure 15: Processing of cobalt-containing nickel-sulfide-ores (Al Barazi, et al., 2018)

3.3 Cobalt recycling

Same as lithium, cobalt also has its largest recipient in the world battery markets. According to different studies, roughly 57 [%] of the world's consumed cobalt landed in batteries („State of the Cobalt“, 2021). The second largest cobalt consumer was nickel-base alloys, with roughly 13 [%] of the worldwide consumption, followed by tool material with roughly 8.5 [%] and pigments with a share of 7 [%] („State of the Cobalt“, 2021). The distribution of the consumed cobalt by the area of application illustrated in Figure 16. A total amount of 129,110 [t] of cobalt was produced in 2020 (Reichl, Schatz, 2022), that means that 73592.7 [t] of cobalt were used in battery production. Therefore, the main focus of recycling cobalt is the recycling of batteries. A predicted increase of 30 [%] in cobalt consumption in the electric vehicle („State of the Cobalt“, 2021) and thereby battery market supports the interest of mainly focusing on the recycling of cobalt out of batteries. According to the USGS, in 2021 24 [%] of the estimated cobalt consumption was out of recycled, cobalt-containing scrap („Cobalt“, 2022). This is already a strong number, but it needs to increase in order to feed the world's hunger for cobalt and to avoid a growing monopolism by primary cobalt suppliers on the world's raw material markets.

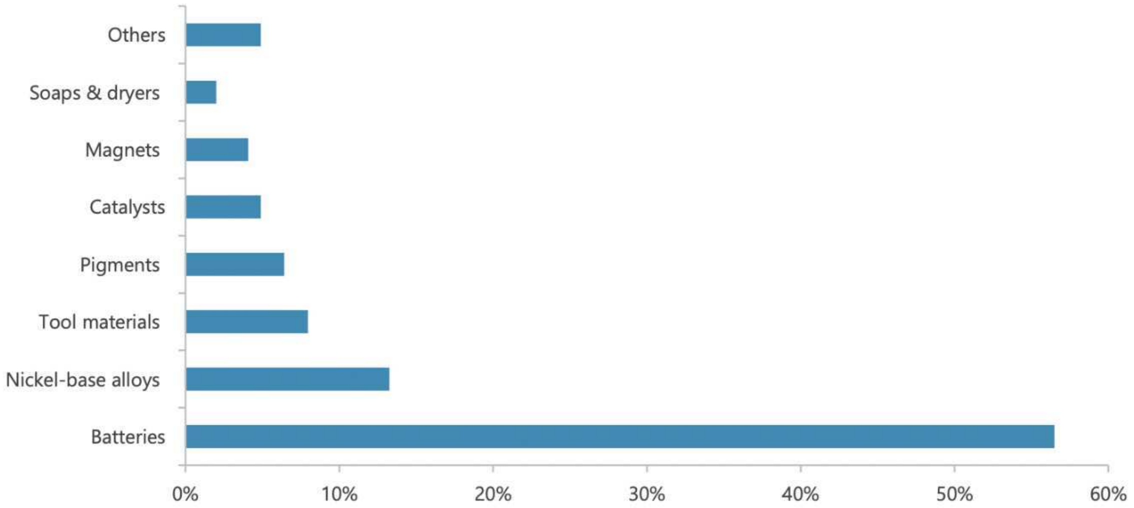


Figure 16: Worldwide cobalt consumption by the area of application („State of the Cobalt", 2021)

However, the recycling of cobalt out of LIBs is already described in chapter 2.3.1 and its subsections. In these chapters, proper disassembly, mechanical processing, and metallurgical treatment are already described in a detailed way.

3.4 Potential of the primary and secondary extraction of cobalt

Cobalt is a Critical Raw Material that is crucial for modern society and most of it is mined in the DRC, Australia and Indonesia. This leads to a strong dependency not only in the EU but also in most industrialized countries who have the aim to expand E-mobility. In this chapter, possibilities to decrease the dependency of such countries are considered as well as the opportunities and possibilities of cobalt mining and recycling within the EU.

3.4.1 Mass flow of cobalt-containing raw materials in Europe

Currently, Finland is the only country within the EU that mines and processes cobalt. Around 2,000 [t] per year are mined in the Scandinavian country. This equals roughly 1.5 [%] of the world's total cobalt production from primary resources (Barrera, 2021).

The consumption of cobalt is calculated in two different forms: cobalt ores, concentrates and intermediates, and refined cobalt. The annual consumption of cobalt ores and concentrates, according to the Critical Raw Material Factsheets 2020 of the European Commission, was 13,856 [t] per year (El Latunussa, et al., 2020). The import reliance of the EU on these products was 86 [%], which equals an import of 11,916 [t] of cobalt from non-EU-states. 14 [%] of domestic production was generated in Finland. Considering refined cobalt, the EU consumed 17,585 [t] per year, of which 9,728 [t] were generated by domestic production and 7,857 [t] were imported (El Latunussa, et al., 2020).

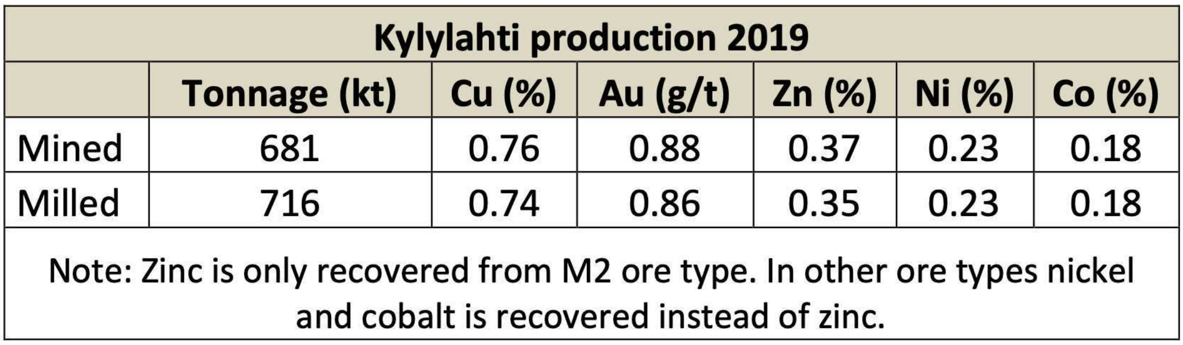
This shows that the EU has a strong dependency on foreign importers, as the domestic cobalt supply covers only 14 [%] of the demand for cobalt ores, concentrates and intermediates. Nevertheless, talking about refined cobalt products, the dependency is not as high, as the EU covers 9,728 [t] of 17,585 [t] of the refined cobalt consumption with domestic production (El Latunussa, et al., 2020).

3.4.2 Production and resources of already existing mines

Cobalt is mainly mined as a by-product of copper and nickel mining since it usually occurs together with these two metals. There is only one mine worldwide that produces cobalt as a primary product. In this chapter, we have a closer look at mines within the EU that already mine and process cobalt.

3.4.2.1 Kylylathi mine Finland

The Kylylathi mine in Finland is a polymetallic underground mine in which copper, gold, zinc, nickel, cobalt and silver occur in different mineralogical compounds (Malmberg, 2019). The mine is located in a town called Polvijärvi in eastern Finland and the mining activities take place in depths of 150 – 810 [m] below the surface (Malmberg, 2019). The mine is owned and operated by the Boliden Kylylathi company. Additionally, the Mondo Minerals B.V. company owns mining licenses in the north of the Kylylathi licenses, but they have an agreement with the Boliden company, which allows them to explore and mine raw materials out of the Mondo-owned area (Malmberg, 2019). In 2019, the Kylylathi mine generated 681,000 [t] of ore, of which the cobalt content was approximately 0.18 [%]. This corresponds to a produced tonnage of roughly 1,226 [t] cobalt (Malmberg, 2019). The mine´s total ore production is depicted in figure 17.



Kylylahti production 2019						
	Tonnage (kt)	Cu (%)	Au (g/t)	Zn (%)	Ni (%)	Co (%)
Mined	681	0.76	0.88	0.37	0.23	0.18
Milled	716	0.74	0.86	0.35	0.23	0.18
Note: Zinc is only recovered from M2 ore type. In other ore types nickel and cobalt is recovered instead of zinc.						

Figure 17: Total ore production of the Kylylathi mine (Malmberg, 2019)

3.4.2.1.1 Legal and environmental circumstances

As the mine is located in an area that is roughly 2 kilometers away from Polvijärvi´s city center, legal and environmental circumstances are of high importance, as the mining activity could have a harsh influence on the people and the environment of the region. Thus, in the following quote, legal influences on the mining operations are described very well by the Boliden company.

> *The land area footprint affected by mining and associated activities is estimated to approximately 890 ha in Kylylahti and 1500 ha in Luikonlahti. Numbers are based on current practice in environmental permitting process including 500 m buffer zone around the mining licenses and adjacent, relevant lakes and rivers (Polvijärvi lake and Viinijoki river in Kylylahti and mixing zone towards the Rauanjoki river south of Luikonlahti). Boliden owns surface right only for mining license areas i.e. 670 ha.* (Malmberg, 2019, p. 9)

Further, due to the very close location of the center of Polvijarvi to the Kylylathi mine, a large part of Kylylathis footprint area is populated. The remaining land is mainly used for forestry and agriculture. A complete vice versa situation is in Luikonlahti, where the majority of footprint area is used for forestry. According to the Finnish Mining Act an annual excavation fee has to be paid for the Kylylahti mining area landowners (mining area does not include auxiliary areas) (Malmberg, 2019). This excavation fee is divided into two different criteria. The first criterion determines that a fixed, hectare based fee which is 50 [€] has to be paid. The second criterion states that 0.15 [%] of the sales revenue of the concentrates produced during the year has to be paid (Malmberg, 2019). Moreover, the criteria define that *“Boliden holds and maintains all of the necessary environmental permits for mining and concentrating the Kylylahti deposit.”* (Malmberg, 2019, p. 12). The current permit allows Boliden to mine and concentrate up to 800 kilotons of ore per year. The environmental permits for the area of Kylylahti and Luikonlahti were reviewed in 2016 and both are still valid (Malmberg, 2019).

This shows that the Boliden company strives to maintain a good relationship with the residents and the environment, as they give their best to support residents financially whilst caring about the environment of the area. This helps the company to maintain the “social license to mine” and is a key to the mine’s future. Only if the acceptance in public is given a project like this can proceed, and that is important, as Kylylathi is one of the most important cobalt providers in the EU.

3.4.2.2 Kevitsa mine Finland

The Kevitsa mine is an open pit mine located at Sodankylä, which is approximately 140 [km] north of the arctic circle in Lapland, Finland. According to diverse Finnish regulations, the Boliden Kevitsa Mining Oy – BKMOY owns the land within the mining concession (Berthet, 2020). Previously, the land was under the control of the Finnish State Forestry Commission, which is the major landowner in the region. However, the BKMOY does not only own the land; they are also the operating entity. They own valid mining concessions for an area of 14.13 [km^2] and have applied for an extension of their already existing concessions of 4.01 [km^2] (Berthet, 2020). Furthermore, the BKMOY has also applied for ore prospecting permits for an area of 15.06 [km^2]. This shows that even though the annual production is already very high, the Boliden company is still trying to expand its mine.

In 2020, the mined and processed ore tonnage was 9,489,000 [t] (Berthet, 2020), which is an increase of 1,800,000 [t] compared to 2019. Mentionable at this point is that the design capacity of the processing facilities is 9,900,000 [t] per year, so the Boliden company uses its facilities at nearly full capacity (Berthet, 2020). In 2020, the total milled material was 918,500 [t] (Berthet, 2020), of whom 24,294 [t] ended up as copper concentrate and 3,108 [t] as nickel concentrate. This equals a “total revenue per element” of 44.1 [%] for copper and 32.1 [%] for nickel. The revenue per element for cobalt was 1.2 [%] in 2020 (Berthet, 2020).

The mining method used to mine raw materials is a conventional “truck and shovel” method. As there have already been mined in two stages, the Boliden company is currently doing a feasibility study of a possible expansion for an additional pushback, which will be stage 5 (Berthet, 2020).

3.4.2.2.1 Legal and environmental circumstances

As Boliden is willing to expand their Kevitsa site, as one can see, due to their permissions for mining and their application for new mining permits, it is also important that the environmental standards are held high. Therefore, the Finnish authorities wanted a new application for an environmental permit by August 2021 (Berthet, 2020). Until now, the outcome of this application is not available for the public.

3.4.3 Project status and exploration of possible cobalt deposits

As mentioned earlier, the EU currently has a cobalt production of roughly 2,000 [t] per year, which leads to a high dependency on foreign cobalt, as the demand within the EU is way higher than the production, as one can read in the chapter 3.4. However, to reduce the EU´s cobalt dependency on global players like the DRC, many exploration projects are ongoing. It is no secret that European geology is not favorable for cobalt mining, but the much-needed raw material still occurs very often in combination with nickel and copper. Therefore, further investigation of cobalt-containing deposits mainly goes hand in hand with copper and nickel production, which is already well established in Europe.

3.4.3.1 Hautalampi project Finland

The Hautalampi mine is located in the Outokumpu municipality, which is an area in eastern Finland. The mine is only 2 [km] away from the city center of Outokumpu and about 350 [km] northeast of Helsinki. It is owned by Finncobalt Oy, which acquired the mine in 2016 as “Vulcan Hautalampi Oy”. Since May 2020, Eurobattery Minerals AB has financed the development of Finncobalt Oy and subsequently earned the right to purchase all of the Finncobalt shares. However, by now the property is covered by a valid mining concession of the Finncobalt company. The total area for which the document is valid is 283.5 [ha].

3.4.3.1.1 Project status and mineral resource estimates

The current status of the Hautalampi project is described very well by the AFRY companys author, Ville-Matti Seppä, as follows.

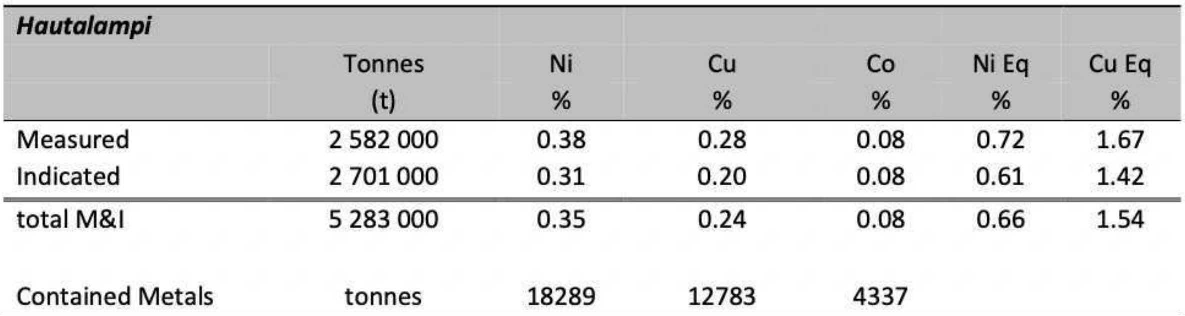
> *The Hautalampi Project is an advanced exploration project that has seen extensive exploration throughout the years. The recent development includes core drilling for metallurgical sampling 2017-2018, which was followed by the flotation test work by GTK Mintec laboratories. Commercial grade Cu- and Ni- Co-concentrates were produced. Further Ni-Co-concentrate leaching test work aiming for battery chemicals production was done by Outotec Oyj.* (Seppä, 2021, p.9)

All these tests succeeded and confirmed that the mineralization at the Hautalampi mine is suitable for battery chemicals production. By now, the deposit has an environmental permit for underground mining and an ongoing appropriation for mining lease. Further, in the autumn of 2020 the company commenced a new environmental impact assessment for the project, which includes underground mining and a on-site ore processing and battery chemicals production plant (Seppä, 2021).

The current status seems to be promising, as an environmental permit for underground mining is already given. However, not only the legal permits have to proceed in a positive way, once planning such a project. The mineral resources in the area of mining need to be mineable in an economic way:

> *The data that has been used for this work has been collected and compiled during the last mineral resource estimate work done by Outotec (Finland) Oy, dated 15th March 2009, and from the latest drilling campaign conducted by Finncobalt Oy in 2020. The estimate has been prepared and reported in accordance with the recommendations of the 2012 Australasian Code for Reporting of Mineral Resources and Ore Reserves (JORC 2012).* (Seppä, 2021, p.9)

The resulting data is shown in Figure 18. The average cobalt content is 0.08 [%], which equals about 4,337 [t] of cobalt that can be mined once this project has started. This might not sound like a large amount but compared to the currently available amount of cobalt within the EU´s mines, which mainly are located in Finland (e.g Hautalampi project) it would be a great push towards less dependency on the cobalt of the DRC.



Hautalampi	Tonnes (t)	Ni %	Cu %	Co %	Ni Eq %	Cu Eq %
Measured	2 582 000	0.38	0.28	0.08	0.72	1.67
Indicated	2 701 000	0.31	0.20	0.08	0.61	1.42
total M&I	5 283 000	0.35	0.24	0.08	0.66	1.54
Contained Metals	tonnes	18289	12783	4337		

Figure 18: Mineral resources estimated at the Hautalampi mine (Seppä, 2021)

3.4.3.1.2 Environmental impact assessment

In August 2020, the Eurobattery Minerals company first commenced an environmental impact assessment for the Hautalampi project. The purpose of such an assessment is to generate proper information on the environmental impacts of such a project. This is very important in terms of the decision making process for such a project, but also for the public stakeholders as they have an opportunity to participate in and affect ongoing processes. An environmental impact assessment must be conducted for all mining projects and is defined by law and consists of a strict procedure. This procedure is explained very well in an article by “EURO BATTERY MINERALS” („Hautalampi project environmental“, 2020).

> *The Environmental impact assessment procedure forms part of project planning and is conducted before any decisions are made to officially approve a proposed project. The Environmental impact assessment has two main phases resulting in the publication of an Environmental impact assessment (EIA) programme and an report. Arrangements for participation play an important role in both phases. The EIA programme will be published and a public hearing will be organised. All relevant stakeholders have a right to give their view of the planned EIA. The EIA procedure concludes with a view and justified conclusion provided by the coordinating environmental authority.* („Hautalampi project environmental“, 2020)

However, the most essential steps in an EIA include an assessment about the current state of the environment, definitions of project alternatives and assessments of their environmental impacts and a comprehensive picture of the projects impacts and implementation alternatives, presented with assessments of the scale and significance of such impacts, plans for the mitigation of detrimental impacts and the publication of an accurate EIA report. This report must assess impacts on nature, human beings and the built environment and cover exceptional situations, environmental accidents, and means to mitigate adverse impacts. („Hautalampi project environmental“, 2020)

As such a procedure is not always easy to understand in a written way, Figure 19 gives a visualization of how the procedure works.

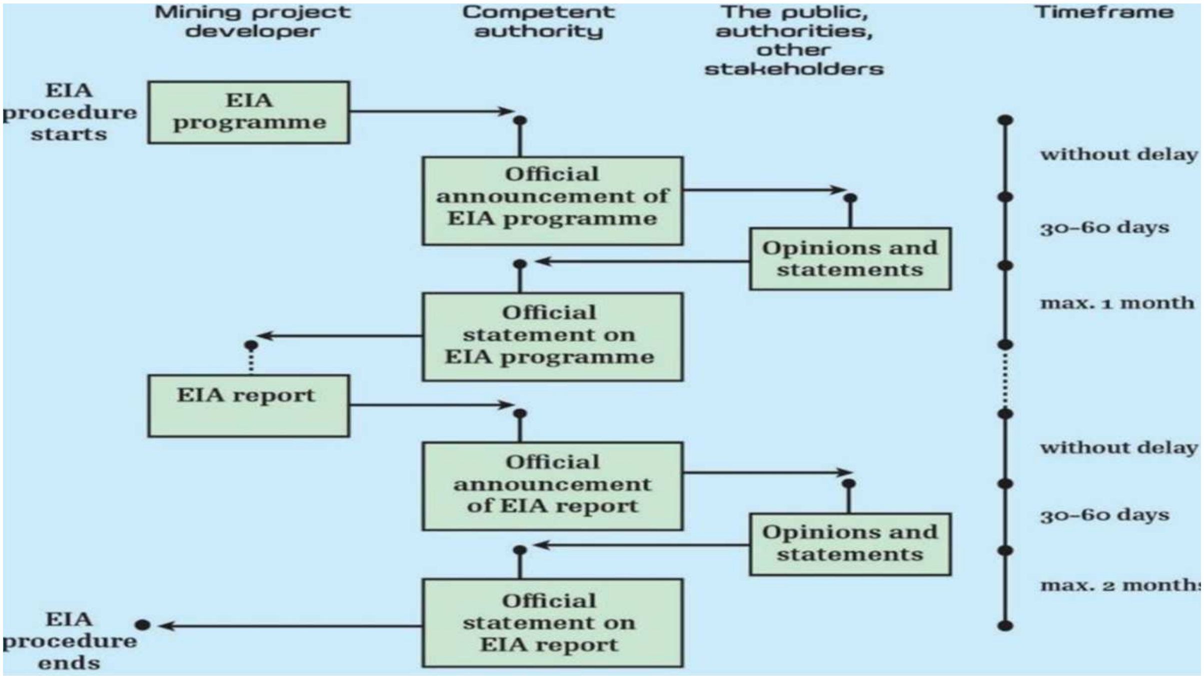


Figure 19: Environmental impact assessment procedure of the Finnish environment institute („Hautalampi project environmental“, 2020)

However, in September 2022 Finncobalt Oy received a request to provide additional information for the Hautalampi project EIA report. The request was made by the “North Karelia Centre for Economic Development, Transport and the Environment”. According to “News – Powered by CISION”,

> *The complex nature of the former copper mine site requires more information on the current environmental situation to be submitted as a part of the Environmental Impact Assessment. The authorities also require some more detailed technical information, especially about the proposed Tailings Storage Facilities.* („Update on the“, 2022)

This shows how intensive and long such assessments can be.

3.4.3.1.3 Resume

Compared to the lithium projects, which were described in chapter 2.4.2, the Hautalampi is not confronted with such large resistance against the project by the public. This could have its source in very transparent EIA´s and/or in the acceptance of Finnish people towards mining operations, as Finland is a country with mining tradition. However, the second is only an assumption and there have been protests in the northern part of Finland against mining activities, as they harm the northern European wilderness, such as lakes, mountains, and animals that settle in those areas, in the opinion of many residents. However, the project seems to be promising as the area provides large amounts of different mineable raw materials. Also, great and transparent EIA`s promise an early start of the mining operations at the Hautalampi project.

3.4.3.2 Juomasuo project Finland

The Juomasuo deposit is a Gold and cobalt deposit that is part of the so-called “Kuusamo Schist Belt”, located about 700 [km] north-east of Helsinki and 45 [km] north of the Finnish town of Kuusamoin („Kuusamo Schist Belt“, n.d.). The Kuusamo Schist Belt, and thus the Juomasuo deposit, are situated in the “Kuusamo – Kuolajärvi orogenic Au metallogenic district”, which contains several epigenetic gold and cobalt deposits and occurrences, of which the Juomasuo is the largest („Kuusamo Schist Belt“, n.d.). In Figure 20, a geological map shows the location of the Juomasuo deposit within the Kuusamo belt (KB) (Vasilopoulos, et al., 2021).

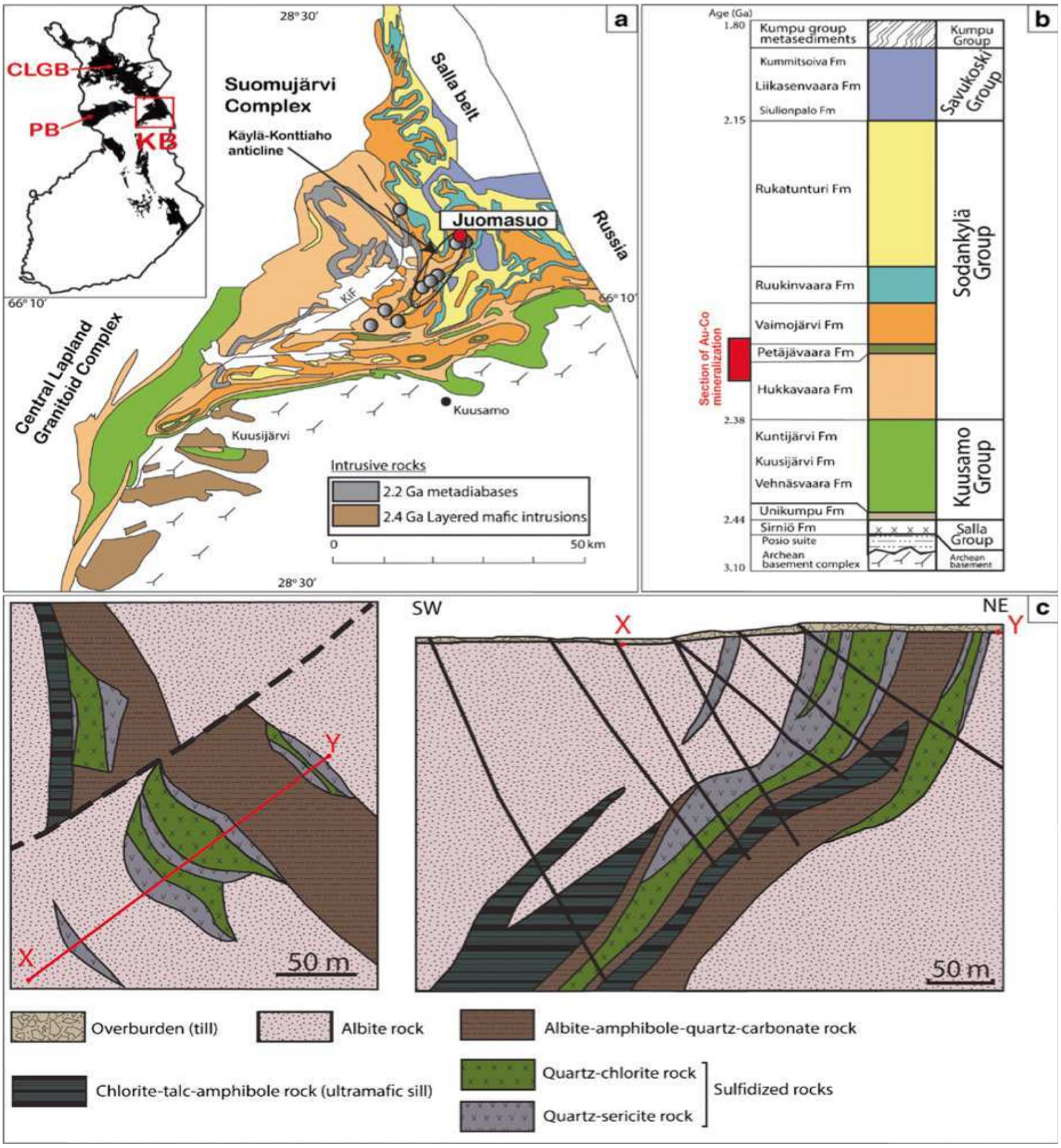


Figure 20: Geological map of the Kuusamo belt showing the Juomasuo deposit (Vasilopoulos, et al., 2021)

3.4.3.2.1 Project status and mineral resources estimation

In the late 1950s, the two Finnish companies Suomen Malmi and Outokumpu Oy began extensive mineral exploration in the Kusamo area leading to the discovery of several deposits. The exploration efforts for gold, iron and uranium were continued further by companies such as Kemi Oy and Rautaruukki Oy. Twenty years later, the Geological Survey of Finland (GTK) took up exploration and research activities in the area. These efforts led to the discovery of the Juomasua deposit in 1985 using airborne magnetic and electromagnetic surveys. The mining rights for this deposit were acquired by Outokumpu Oy in the early 1990s. The company continued by conducting first test mining activities and a prefeasibility study. After changing ownership several times, the mining activities have since ceased and no other deposits in the Kusamo belt have been exploited yet (Vasilopoulos, et al., 2021).

The Juomasuo deposit contains two main ore types, which are a lean cobalt ore on the one hand and a gold-cobalt ore on the other hand (Vasilopoulos, et al., 2021). The ore, which occurs mainly as cobalt ore, shows a richness in pyrrhotite with a minor part of pyrite and chalcopyrite. The gold-cobalt ore, on the other side, shows a richness of pyrite only (Vasilopoulos, et al., 2021). The total mineral resource estimate of the deposit is roughly 2,370,000 [t], grading 4.6 [$g \cdot t^{-1}$] gold and 0.13 [%] cobalt. Additionally, a 5,040,000 [t] deposit containing 0.12 [%] cobalt is in the area of the Juomasuo deposit (Vasilopoulos, et al., 2021). Now, the project is still in an advanced exploration stage (Guzik et al., 2021), but once mining operations start, the Juomasuo deposit will contribute to the EU´s independency in the cobalt market.

3.4.3.2.2 Resume

> *The Juomasuo mine would increase the European production of cobalt respectively, for the European battery industry, also contributing to the traffic electrification and climate change mitigation. If accomplished, the Juomasuo mine will be the fourth cobalt mine in Finland, the only country in the EU producing primary cobalt. The project would also contribute to the reduction of the EU's dependency on imported battery minerals according to the EU's Green Deal Program.* (Guzik et al., 2021)

This citation shows how important the exploration and further the ongoing mining procedure of cobalt-containing ore is for the EU. The Juomasuo mine would supply the European market with high-grade cobalt ore, which is crucial for the independence of the global players in the worldwide cobalt markets. If it was possible to mine all the in the mine containing cobalt, this would result in an amount of 9,129 [t] of pure cobalt if one uses the data given in chapter 3.4.2.2.1.

3.4.3.3 Further possibilities and potential of cobalt extraction within the EU

As there does not exist a single deposit in Europe that mainly contains cobalt, it is tough to gain proper information about the specific cobalt extraction or exploration status of single mines. However, in this chapte further possible cobalt deposits are taken into account.
Talking about the possibilities of cobalt extraction within the EU, one cannot ignore Sweden and its possible as well as its already-known deposits. In total, there are roughly 20,000 [t] of cobalt lying in Swedish deposits (Barrera, 2021). Until now, the critical raw material has been mined at several mines such as Los, Tunaberg, Gladhammer, and Kleva (Barrera, 2021). However, exploration operations with the goal of opening new mines or re-opening already existing mines are in an upward trend since cobalt has become more and more crucial for the Swedish and European electric industry. Projects whose exploration is widely advanced now are the Haggan Vanadium project of Aurora energy and the Ronnbacken nickel project of Archelon. Both projects aim to mine cobalt as a by-product (Barrera, 2021). Further, the Australia-listed Talaga Resources has exploration permits at Kiskamarvaara and Ahmavouma (Barrera, 2021). The company's Kiskama copper-cobalt project has an estimated resource of 7,700,000 [t] at 0.04 [%] cobalt, which makes it the largest cobalt deposit in Sweden (Barrera, 2021). Besides the Kiskama, the Talga company owns other high-graded cobalt projects in Sweden which are at an earlier stage of exploration, such as the Aitik East project (Barrera, 2021).
Another country that could be a big player in the European cobalt industry is Greece. In the south European country, lateritic reserves of almost 50,000 [t] of cobalt and mineral resources with an additional 79,000 [t] of cobalt exist (Barrera, 2021). The main laterite deposits of Greece are Kastoria, which has resources of 8,700,000 [t] at 0.06 [%] cobalt, Agios Ioannis, with a resource of 43,600,000 [t] at 0.05 [%] cobalt, and Evia, which has a resource of 228,300,000 [t] at 0.05 [%] cobalt content (Barrera, 2021). All these mines are currently operated by the Larco company. However, cobalt is not mined as a main product in any of these mines, as they are all focusing in nickel production.

3.4.4 Summary of cobalt mining in the EU

Just as lithium, cobalt is already mined in the EU, but only in a very small amount. New cobalt deposits need to be explored and mined to achieve more and more independence from the DRC. Currently, the EU consumes 13,856 [t] of cobalt concentrates per year, as stated in chapter 3.4. By now, only 2,000 [t] origin from the EU itself. Therefore, a rise in cobalt production within the EU is crucial to gain independence. Explored deposits, such as those in Sweden and Greece have potential to be mined soon. This would increase domestic cobalt production significantly and it would reduce the dependency on cobalt concentrates significantly. However, not only primary cobalt products are of high interest within the EU, but also refined products are a big player in the world's cobalt markets. As written in chapter 3.4, 27 [%] of these are not domestic. Increasing domestic cobalt production could decrease this number as well.

3.4.5 Environmental and social discussion

In mining, environmental and social aspects which come along with the mining process always need to be considered. However, unlike lithium, no severe protests against potential or current cobalt projects can be found. This could have a couple of reasons: As mentioned, cobalt is always mined as a by-product of nickel or copper. As these two raw materials have a strong tradition in large-scale mining projects worldwide, the topic "cobalt" may be no trigger point for environmental protesters. Additionally, there are no ongoing protests against ongoing copper mines in the EU. However, there is no other apparent reason why there is such a big protest movement against lithium projects but not against cobalt projects. The only protests which could be in the context of cobalt mining are overall anti-mining protests, which are focused on topics such as the greenwashing of the industry or environmental aspects of overall ongoing mining activities.

Considering the socio-economic impacts, the opening of new cobalt mines would result in many positive aspects. They would strengthen the "cobalt location EU", new projects would provide new working places and the dependency on African cobalt would be reduced. The opportunity for new jobs in the mining business would go hand in hand with the economic development of rural mining areas in the north of Scandinavia, as they would lead to settlements for schools, stores for daily needs, doctors and many more in the long run. Additionally, new mining pits would lead to the settlement of heavy industry in the mining area, which further leads to many new working places. This would be a positive development in times of high inflation and unemployment, especially in rural areas. Unfortunately, no specific data can be found on how many jobs the mentioned projects could offer. Nevertheless, it is assumeable that large-scale mining operations - depending on the degree of automotation - go hand in hand with a large amount of newly provided jobs. Finally, one must mention that all possible cobalt projects are not as far developed as lithium projects, such as the Jadar project in Serbia. A potential protest of farmers on topics such as water pollution could be possible once the opening of new mines is planned in further detail. Nevertheless, by now there is no large resistance against potential mining projects in Scandinavia spotted.

3.4.6 European potential in the area of cobalt recycling

Regarding the recycling of cobalt, one can see that the recycling of old LIBs and other batteries is the go-to topic, similar to the recycling of lithium. Therefore, the recycling of cobalt-containing batteries is the main topic in this chapter. As already mentioned, the recycling procedure of batteries is described in chapter 2.3.1 and its subheadings and, therefore, not further considered in this chapter, such as battery recycling projects and their European potential, as they are described in chapter 2.4.4 and its following subsections. Nevertheless, it is important to provide numbers in terms of cobalt recycling out of LIBs and other batteries, as these secondary raw materials are the largest provider of secondary cobalt.

According to the British Cobaltinstitute, in 2020, 10,600 [t] of cobalt were recycled worldwide. Furthermore, the organization reports that 65 [%] of the recycled cobalt comes from recycled batteries, which makes it a total of 6,890 [t] („State of the Cobalt“, 2021). However, for the EU, there are no quantities available that give information about how much cobalt is recycled out of batteries (El Latunussa, et al., 2020). The amount of recycled cobalt can roughly be estimated, as there is information given by the factsheets of the European commission that about 10,410 [t] of batteries are recycled in Europe annually. Belgian Umicore recycles roughly 7,000 [t], Akkuser in Finland 1,000 [t], Accurec in Germany 2,000 [t], Recupyl and SNAM in France recycle combined about 410 [t] of LIBs (El Latunussa, et al., 2020). Umicore recycles not only LIBs, but also nickel-metal hydride batteries, which differ significantly in the amount of cobalt compared to LIBs. As LIBs contain about 5–20 [%] of cobalt, nickel-metal hydride ones contain 3–5 [%] cobalt (Kim et al., 2021). Nevertheless, this shall not affect the earlier mentioned estimation of the totally recycled cobalt amount out of batteries. If an average cobalt amount of 12.5 [%] is assumed within a LIB, this will result in a total amount of 1,301 [t] of cobalt, which is concealed within EU recycled batteries. A huge amount that exceeds the annual cobalt production of the Kylylathi mine in Finland. Further, if one compares this tonnage with the total amount of cobalt recycled out of batteries worldwide, which is 6,890 [t], one can see that 19 [%] of the worldwide cobalt recycled out of batteries comes from the EU. Compared to the market share of primarily produced European cobalt, which is 1.5 [%] (El Latunussa, et al., 2020), this is a very strong amount that could help gaining more independence from non-European cobalt.

However, the recycling of cobalt from batteries needs to be improved, as the annual demand for cobalt will increase by 350 [%] compared to 2022, mainly driven by the E-mobility sector („Access to Cobalt“, 2022). According to the “Cobalt Institute”, 67 [%] of battery cobalt in the EU could be recycled by 2050 („Access to Cobalt“, 2022). It will be crucial to improve the European battery recycling capacities. Nevertheless, as there will be a strong increase in the production of cobalt-containing products, there will also be a great chance in the recycling potential of cobalt within the EU if proper and higher recycling capacities are built, as already stated befor.

Additionally, the recycling of cobalt out of magnets, hard metal and other cobalt-containing alloys and scraps needs to be taken more seriously. According to DERA, there was no proper data about the recycling rates of such materials given by the year 2018 (Al Barazi, et al., 2018). A tracking improvement to gain more information about the amount of cobalt recycled out of those materials is crucial to improve future recycling techniques and processes. No further interpretation can be made due to a lack of data.

3.5 Usage of cobalt raw materials in European industries

As a consequence of its many specific properties, cobalt has many areas of application. However, one can divide them into two main segments, which are cobalt metals on the one hand and cobalt chemicals on the other hand. In 2017, 63 [%] of the cobalt demand was used for chemicals and 37 [%] for metallic products (Al Barazi, et al., 2018). Then and now, the most important field of application of cobalt-containing products is the production of LIBs, as discussed earlier. Combined with nickel-metal hydride and nickel-cadmium batteries, the battery sector had a share of the cobalt market at 46 [%](Al Barazi, et al., 2018). The second largest cobalt consumer, with a market share of 16.5 [%] in 2017, were superalloys, followed by carbides and Diamonds with a share of 8.5 [%] and magnets with a share of 5.1 [%] (Al Barazi, et al., 2018). A proper listing of the different areas of application of cobalt-containing products can be seen in figure 21.

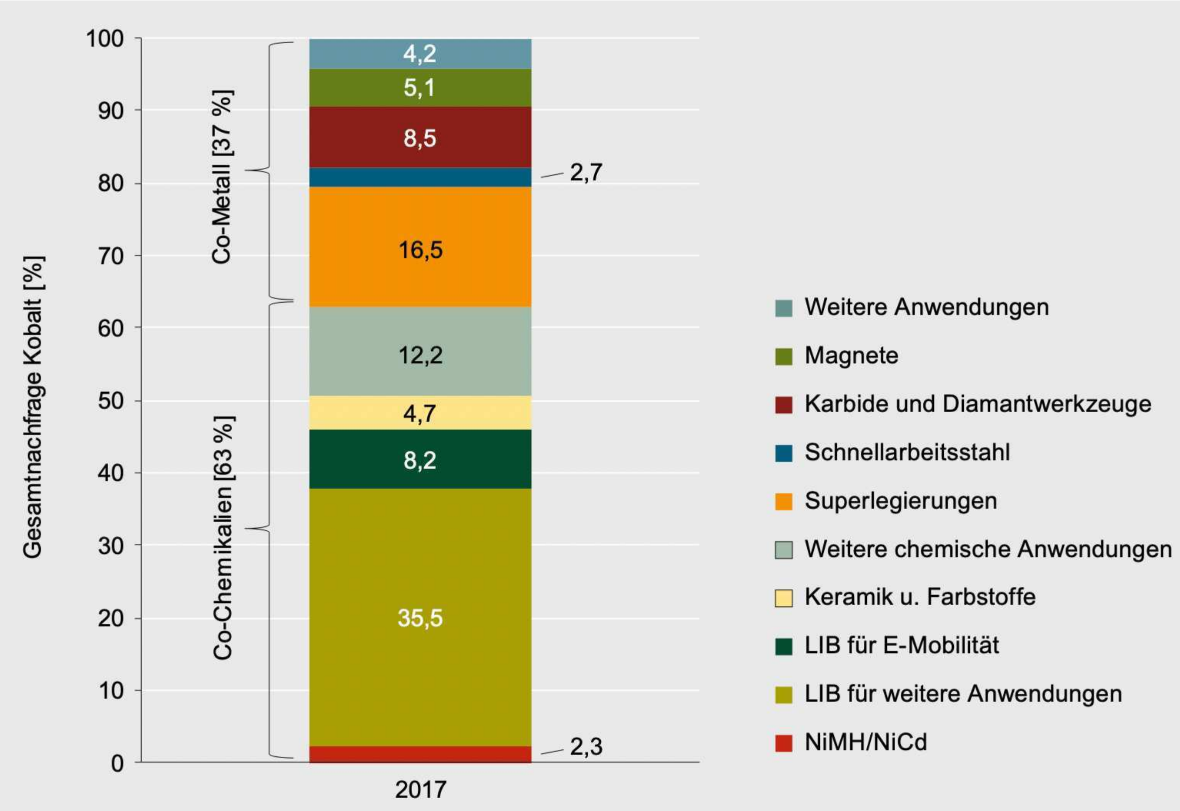


Figure 21: Field of application for cobalt products in 2017 according to DERA (translation see chapter 9) **(Al Barazi, et al., 2018)**

3.5.1 Cobalt in the battery industry

As the battery industry is the largest consumer of lithium, research on the function, need and economic value of lithium in different batteries needs to be taken under research. It is important to understand how the raw material works and if it is really that important for society and the economy as assumed.

3.5.1.1 Design and function of a LIB

The basic function of a LIB can be found in chapter 2.5.1.1.

3.5.1.2 The function of cobalt in a LIB

As written in chapter 2.5.1.1, a LIB consists of four main parts. A deeper look at the battery electrodes needs to be taken to understand the role of cobalt within a LIB. A rechargeable LIB basically consists of two electrodes that are immersed in an electrolyte solution and separated by a permeable polymer membrane (Clemens, 2018). Whilst charging a battery, lithium ions pass from the positive cathode through the polymer membrane towards the negative anode. During the discharging of the battery, lithium ions get transferred back from the anode toward the cathode. During this process, lithium ions give up electrons to the anode, which travel via an external circuit to power an electronic device before returning via the circuit to the cathode (Clemens, 2018). At this point, it is important to have a proper look at the electrochemistry of a LIB. The most common anode material in a LIB is carbon graphite, as it has an ordered layered structure that can accommodate and store lithium ions between its layers (Clemens, 2018). As the working voltage of a battery is always determined by the difference in electrochemical potential between the cathode and the anode, the cathode needs to be another material than graphite. The cathode works in a way that it stores lithium ions through electrochemical intercalation, which is a process by which lithium ions are inserted into or removed from lattice sites within the cathode material (Clemens, 2018). This brings us to the question, “why do we need cobalt”?

One of the simplest cathode materials is lithium-cobalt-oxide (Li-Co-O_2). Senior scientist Daniel Abraham from the “Argonne National Laboratory” explains why that is the case:
“In a lithium ion battery, what we are trying to do during charging is to take the lithium ions out of the oxide and intercalate or insert them into a Graphite electrode. During discharging, exactly the opposite happens.” (Clemens, 2018) Abraham further explains the role of cobalt within a battery as follows.

> *When the lithium ion is taken out of the oxide (in the cathode), the lithium ion has a positive charge, so the cobalt changes its oxidation state, so that the oxide stays electrically neutral. A small amount of the cobalt changes its electronic character from oxidation state +3 to +4 to account for the removal of the lithium ion* (Clemens, 2018).

Cobalt, which is a so-called transition metal, has the job of compensating for the charge in the cathode when a lithium-ion arrives or departs. The main ability of such transition metals, which are needed within a battery, is the ability to change valence to maintain neutrality (Clemens, 2018). According to Abraham,

> *lithium–cobalt-oxide is what we call an intercalation compound; the lithium, the cobalt and the oxygen are arranged in two-dimensional layers. The lithium is in one layer, then a layer of oxygen, cobalt in another layer, and then you have another layer of oxygen and another layer of lithium, and that is how the material structure is arranged. In an intercalation compound, you should be able to take the lithium out and the framework structure should remain unchanged. If the structure changes, it becomes very difficult to put the lithium back in* (Clemens, 2018).

The cobalt-enhanced structure can withstand the removal of about 60 [%] of the lithium before the structure begins to change. A replacement of cobalt through nickel would still create an intercalation structure. However, if a significant amount of lithium is removed from a nickel-oxide structure, large amounts of oxygen are released, which can be a fire hazard. According to Abraham, aluminum which holds onto oxygen could be added to the structure to reduce fire hazards. It would stabilize the structure, but it would also lower the cell's electric capacity (Clemens, 2018). However, at least small amounts of cobalt are needed in battery materials, as cobalt helps to increase the battery’s performance (Clemens, 2018). That means a complete substitution of cobalt is not feasible, but a reduction of the cobalt amount down to 10 [%] of the basis amount would be possible whilst still providing the wanted battery properties (Clemens, 2018).

3.5.1.3 Amount of cobalt in different battery types

Like lithium, cobalt is a component of different battery types which contain different amounts. As our focus is on LIBs in the electric vehicle industry, it is important to mention that these industrial batteries can contain anywhere between 4 [kg] and 30 [kg] of cobalt, depending on battery size and application (Goad, 2019). Cell phone batteries vary in their cobalt content, just the same as the ones in the mobility sector. Cell phones can contain anywhere between 5 [g] and 20 [g] of cobalt, depending on size and application as well (Goad, 2019).

3.5.1.4 Technical and financial value of cobalt in the battery industry

In this chapter, the batteries of the Tesla “Model 3” are used as a visualization of how much value cobalt has in the battery industry to provide a proper view of the technical and financial value of cobalt in the battery industry. The current price of high-grade cobalt raw materials is a little lower than the price of high-grade lithium raw materials. According to “YCHARTS”, the US cobalt spot price was 51,515.41 [$] per metric ton („US Cobalt Spot“, 2022). The amount of cobalt, which is built in a Tesla Model 3, is 4.5 [kg] („Panasonic reduces Teslas´s“, 2018). That means that the value of cobalt, which is built into such a battery, is about 232 [$]. Compared to the car price of the standard Tesla Model 3, which is 46,990 [$] (Doll, 2022), that is just a very, nearly insignificant, low-cost driver which makes 0.49 [%] of the overall car price. If one looks at the Tesla Model S from chapter 2.5.1.4, which has a price of 106,440 [$], this cost driving factor compared to the car price is even lower. Therefore, it can be said that the financial value of cobalt which is built into the battery of a Tesla Model

3 has no high value. Additionally, the technical value of cobalt in Tesla batteries gets lower each year, as Tesla's goal is to produce cobalt-free batteries. As this works out very well, the technical value of cobalt in such batteries is not high anymore, other than is the case with lithium. The substitution of cobalt in the battery industry is further described in chapter 3.5.1.5.

3.5.1.5 Possibilities to substitute cobalt in LIB´s

A company that had great success in developing and using cobalt-free batteries is Tesla. They claim that half of their vehicles produced in the first quarter of 2022 already use cobalt-free batteries, namely so-called LFP batteries (Lambert, 2022), which stands for lithium-iron-phosphate batteries. Tesla CEO Elon Musk has the goal to shift more and more cars towards the use of those batteries. Traditionally, these batteries are safer and cheaper than common LIBs, but they have one little disadvantage towards their broadly used competitor, which is a lower energy density (Lambert, 2022). That means that they are a little less efficient. This results in a short driving range for the vehicle which uses them. Nevertheless, Tesla claims that they had some great success in improving such batteries and now use them in lower-end and shorter-range cars (Lambert, 2022). For example, the company has already shifted its standard range, Model 3 and Model Y, to LFP-driven vehicles. Additionally, they already announced to shift of all their standard-range vehicles to the LFP drive. After the release of their "Q1 Model", half of the company's vehicles use LFPs by now (Lambert, 2022).

To understand why LFPs are a great alternative to LIBs, which contain a lot of the Critical Raw Material cobalt, it has to be looked at the function of such batteries: LFP batteries use lithium iron phosphate ($LiFePO_4$) as the cathode material alongside a graphite carbon electrode with a metallic backing as the anode (Frith, 2021). Unlike many cathode materials, LFP is a polyanion compound composed of more than one negatively charged element (Frith, 2021). Its atoms are arranged in a crystalline structure forming a 3D network of lithium ions compared to the 2D slabs from nickel manganese cobalt. The LFP battery operates similarly to other lithium-ion batteries, moving between positive and negative electrodes to charge and discharge (Frith, 2021). To understand the function of such batteries in a better way, Figure 22 helps as visualization.

However, phosphate is a non-toxic material compared to cobalt oxide or manganese oxide. What's more, LFP batteries are capable of delivering constant voltage at a higher charge cycle in the range of 2,000–3,000 cycles (Frith, 2021). The energy density of LFP batteries is lower than the alternative of lithium cobalt oxide (LiCoO2) and has a lower operating voltage. In spite of these challenges, it’s impossible to deny the benefits of LFP batteries in EV vehicles (Frith, 2021). LFP is known for its low cost compared to nickel-manganese-cobalt (NMC), for example, as it has an average price that is 70 [%] lower than the NMC. Additionally, they have a longer lifecycle than other LIBs because cells experience slower rates of capacity loss (Frith, 2021). Their lower operating voltage also means that cells are less prone to reactions that impact capacity. With a consistent discharge voltage and lower internal resistance, LFP-powered vehicles can deliver power faster and achieve a higher charge/discharge efficiency (Frith, 2021). Furthermore, LFP is thermally and chemically stable, making it less prone to explosions or fire due to misuse or structural damage. In lithium cobalt oxide batteries, thermal runaway can result from the omission of cobalt with its negative temperature coefficient. Further, no lithium remains in fully charged cells, making them highly resistant during oxygen loss compared to the exothermic reactions, which are typical for other lithium-containing battery cells (Frith, 2021).

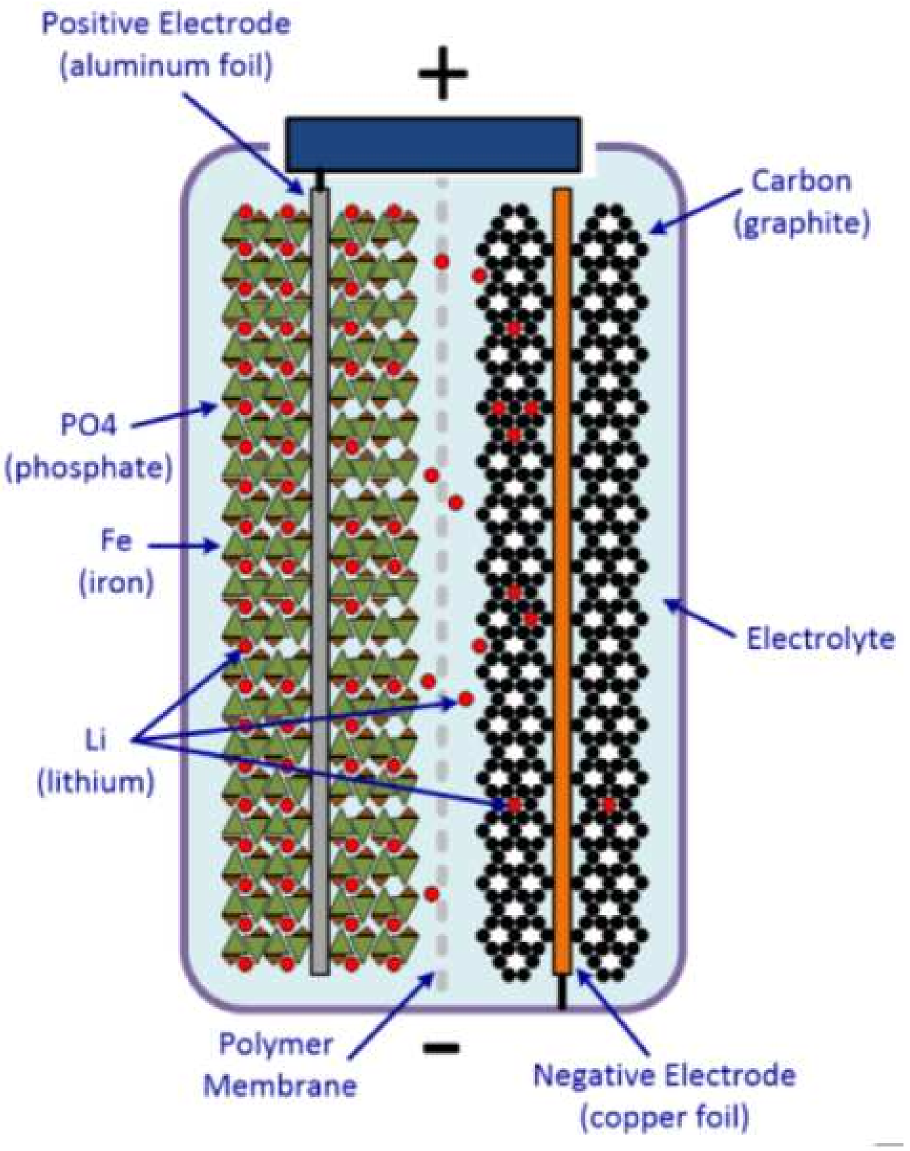


Figure 22: Design of an LFP battery (Frith, 2021)

As depicted in figure 22, LFP batteries seem to have a bright future in the electro-mobility sector, as they are already very advanced and bring more pros than cons with them. In terms of raw material criticality, such batteries are a great and absolutely reliable alternative to cobalt-containing batteries. This technical standard is a great improvement toward the independency of cobalt.

3.5.2 Cobalt in the superalloy industry

As shown in the graph of chapter 3.5, 16.5 [%] of the world's produced cobalt is used for so-called superalloys. Those alloys show great corrosion and heat resistance properties, which make them very important in many industries, such as air- and space technology, the marine industry and medical areas („Kobaltlegierungen“, n.d.). Unfortunately, there was no further information found on the topic of cobalt recycling out of alloys, as most literature found about the recycling of cobalt is about battery recycling itself.

3.5.3 Cobalt in the magnet industry

Cobalt in the magnet industry makes up roughly 5.1 [%] of the worldwide cobalt demand. Cobalt-containing magnets such as samarium-cobalt (SmCo) magnets are the most used ones. They are made of an alloy of about 35 [%] samarium and 60 [%] cobalt with small amounts of iron, copper, hafnium and zircon („What are samarium“, 2022). Further, SmCo-magnets have a wide variety of positive aspects and strengths. Compared to neodymium magnets, they work over a wider temperature range; they have superior temperature coefficients and greater corrosion resistance („What are samarium“, 2022). Therefore, such magnets are used in medical implants, bearings and motors. Unfortunately, there was no further information found on the topic of cobalt recycling out of magnets, as most literature found about the recycling of cobalt is mainly about battery recycling.

4 Critical raw materials fact checks in battery production

In this chapter, a fact check of the relevance of lithium and cobalt within a battery is done to gain a simple but informative overview of how and why we may or may not need those two critical Raw Materials in the car-battery industry. The absolute mass of lithium and cobalt, their costs and the price share of the complete battery is calculated and alternatives for these two raw materials are highlighted. This chapter is a comparison and resume of topics already described in this thesis.

4.1 Total mass of lithium and cobalt

It is very hard to gain exact information about the total mass of lithium built in a car battery, as already written in chapters 2.5.1.3 and 2.5.1.4. According to different sources, the absolute lithium mass built in a Tesla Model S could lie between 10 [kg] (Mittermeier, 2016) and 63 [kg] (Lambert, 2016). Additionally, the amount of lithium that a battery contains depends strongly on the power of the battery. Higher power equals a higher amount of lithium. All these parameters make it very hard to gain information about exact mass values. The same problem occurs with cobalt. Sources claim that electric vehicles have a content of 4 [kg] – 30 [kg] (Goad, 2019) in their batteries, as already described in chapter 3.5.1.3. According to other sources which act more like a question platform, the mass of cobalt in electric vehicle batteries is somewhere between 6 [kg] and 12 [kg], depending on their size. As there are also batteries with only a low cobalt content available on the market, this brings even more variety to the question of how much of the raw material is built into batteries.

As one can see, it is very difficult or barely impossible to gain information on how much of each raw material is exactly built into an electric vehicle battery, as there are varieties of accessible information in terms of battery size, power, model and also development.

4.2 Total material costs of lithium and cobalt

Due to the problems described in chapter 4.1 and the fact that raw material prices change permanently, it is also very hard to calculate the exact value of the raw materials which are built into an electric vehicle battery. However, it is possible to make assumptions in terms of cost reduction of batteries, as one can substitute different raw materials within a battery whilst having a similar mass of the alternative material built in. To gain a rough estimate of how much of a Tesla´s production price is caused by Critical Raw Materials, it is assumed that the amount of lithium in a battery is 63 [kg] and the amount of cobalt is 12 [kg]. This would result in lithium being built in a Tesla for a spot price of 4914 [$], according to chapter 2.5.1.4 (Probst, 2022). Using the numbers of chapter 3.5.1.4 („US Cobalt Spot“, 2022), 12 [kg] of cobalt would result in a spot price of 618 [$]. Talking about the Tesla S with a market price of 106,440 [$] („2022: Tesla Model S“, 2022), as written in chapter 2.5.1.4, one has to additionally take the profit margin of the car into concern. According to German sources, Tesla has a margin of 19.2 [%] („Auto-Hersteller“, 2022), which leads to production costs of the Tesla S – and all other costs until the car can be sold profitable – of 86,003.50 [$]. Out of these production costs, lithium and cobalt have together a share of 5,532 [$], which makes 6.43 [%] of the total production costs of the car, according to the used assumptions. Talking about the Tesla Model 3, the percentage of lithium and cobalt out of the total production costs would even be higher. As one can see, for a Tesla S, using this assumption, the raw material prices would be a third of the profit margin which is a very high number. So as one can see, if lithium and cobalt are built in a Tesla in the highest amount according to various sources, the material price compared to the car price before and after profit margin is high.

4.3 Substitution possibilities of lithium and cobalt in batteries

In chapter 2.5.1.5, the possibility of substituting lithium within LIBs is described. Sodium-ion batteries, which were under research in South Korea in 2020, showed some great success in this area, as their technical, chemical and physical properties are similar to the ones of common LIBs (Freund, 2020). As already mentioned, these batteries are highly developed and their mass application should or could only be a matter of time from a technical point of view. One must consider that also manufacturing processes of car batteries need to be changed and specified to such battery types. Nevertheless, this could be a bright option in terms of lithium reduction and independency not only for the European industry but also for the worldwide car and battery industry.

The possibilities concerning substitution possibilities of cobalt in car batteries are even more developed and already widely used, as described in chapter 3.5.1.5. So-called LFP batteries, which are built and used in a large amount in Tesla´s car batteries, seem to reduce the need for cobalt in electric vehicles more and more (Lambert, 2022). They even could supplant cobalt-containing batteries completely soon, which would be a great step towards cobalt independence.

Both, Sodium-ion and LFP batteries have one very important aspect in common. They would reduce the dependency of the EU on critical raw materials drastically, as lithium and cobalt are mainly needed and used in the battery industry, as it has been stated in this thesis.

5 Conclusions on the possibilities of Critical Raw Material independency

As described in this thesis, there would be great possibilities and options to decrease the dependency on lithium imports from non-EU states. European lithium deposits in Portugal, Spain and Serbia (which is not a member of the EU yet) would provide a massive supply of the needed raw material. Additionally, battery recycling has a huge upwards trend within the EU and is under development. As batteries are the main lithium and cobalt consumers within EU industrial sectors, the recycling of those would also supply secondary raw materials to the European market. More data is needed to make a clear statement of how the EU could supply itself through primary and secondary extraction of cobalt. However, as cobalt is used mainly in battery production, primary and secondary self-supply is not as crucial as is the case with lithium, as there is a current trend that batteries, especially in the mobility sector, are going to be nearly or even completely cobalt-free. This would also result in a strong decrease in cobalt dependency from non-EU states.

As it can be seen, there are great possibilities to reduce European dependency on critical raw materials in the main Critical Raw Material consuming industry, namely the battery industry. If the substitution of lithium and cobalt develops in a positive way, the criticality of these raw materials will decrease significantly. Therefore, further development and research in lithium and cobalt-free batteries needs to be done to improve the development and application of such batteries and to achieve raw material independence in the EU.

6 Personal resume about working on this thesis

Finally, it is my pleasure to make a personal statement on the whole procedure of this thesis. Due to this thesis, my personal interest in the possibilities of developing new points of view on the European raw material market and its possibilities increased. My interest and hope of a possible mining development within the EU increased strongly due to the topics I conducted research on. Furthermore, it was a pleasure to improve my knowledge about many problems which must be solved soon, such as raw material self-supply and recycling possibilities. Nevertheless, I have to be honest when I say that a professional future in the field of research is not where I see myself and where I want to be. I already had this assumption after my bachelor's thesis and it got confirmed after my master's thesis. I am a man whose interest is always to push forward and make an impact on our society. However, in my personal opinion and according to my subjective well-being, this is not in the area of academic research but in the area of practical problem solving, such as mine development and operating management on site. Additionally, I found out that I simply feel happier and more fulfilled when I am working on-site with the possibility of doing outdoor work on a regular basis, just as I do in my current job than being active in the area of research. So through this thesis, I once again proved to myself that a Ph.D. or a further academic career after the master’s program would not be an option for me. Nevertheless, this thesis and especially this topic were very enjoyable to me, as I had a lot of freedom given by my two supervisors Prof. Tost and Dipl.-Ing. Kügerl, in terms of research questions and problems which I wanted to investigate and increase my general knowledge on very relevant future questions which influence the raw material market drastically.

7 List of Figures

8 List of Abbreviations

AIM	Alternative Investment Market
ASM	Artisanal Small-scale Mining
ASX	Australien Securities Exchange Ltd.
BBU	Bleiberger Bergwerksunion
BKMOY	Boliden Kevitsa Mining Oy
CAGR	Compound Annual Growth Rate
CEO	Chief Executive Officer
Critical Raw Material	Critical Raw Material(s)
DERA	Deutsche Rohstoffagentur
DRC	Democratic Republic of Congo
EIA	Environmental Impact Assessment
EU	European Union
EV	Electric Vehicle
GSM	Global Strategic Metals
JORC	Joint Ore Reserve Committee
KMI	Kärnter Montanindustrie GmbH
LFP	Lithium-Ironphosphate-Battery
LIB	Lithium-Ion-Battery
LSM	Large-scale Mining
NGO	Non-governmental Organization
US	United States
USGS	United States Geological Survey

Al	Aluminum
B	Boron
C	Carbon
Cl	Chlorine
Co	Cobalt
Cu	Copper
F	Fluorine
Fe	Iron
H	Hydrogen
Li	Lithium

Mg	Magnesium
Mn	Manganese
Na	Sodium
S	Sulfur
Si	Silicon

g	Gram
kg	Kilogram
s	Seconds
l	Liters
ha	Hectares
K	Kelvin
J	Joule
mol	Mol
V	Volt
°C	Celsius
ρ	Density
m	Meter
cm	Centimeter
km	Kilometer
t	Tons
$	US-Dollar
€	Euro
%	Percent

9 Translations

Rückführung	return
Batteriezellen	battery cells
Mischtank	mixing tank
Filterpresse	filter press
Filtration	filtration
Aufbereitung	processing
Flüssigkeit	liquid
Laugungsmittel	leaching agent
Fällungsmittel	precipitant
Unterkorn	undersize grain
Laugung	leaching
Fällung	felling
Oder	or
Extraktionsmittel	extracting agent
Mehrstufige	multilevel
Solventextraktion	solvent extraction
Gesamtnachfrage	total demand
Chemikalien	chemicals
Metall	metal
Kobalt	cobalt
Magnete	magnets
Diamantwerkzeuge	diamond tool
Schnellarbeitsstahl	high speed steel
Superlegierungen	super alloys
Weiter	further
Anwendung	application
Keramik	ceramic
Farbstoffe	dyes

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