Tangled Up in Blue: Future Cobalt Scarcity and Environmental Effects of Cobalt Usage in Lithium-Ion Batteries

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Dokumenttitel och undertitel

En studie om koboltbrist och potentiella framtida effekter av fortsatt användning av kobolt i litiumjonbatterier

Sammandrag

Målet med denna studie var att undersöka riskerna för koboltbrist och hur dess miljöeffekter kan se ut i framtiden. Detta gjordes genom att skapa tre scenarier baserade på olika framtidsprognoser gällande kobolt till år 2050. *Business as usual* (Scenario I), *Recycling Rate Improvements* (Scenario II) och *Technological Advancements* (Scenario III). Scenario III hade lägst koboltanvändning, 3,68 megaton, medan Scenario I hade högst, 10,8 megaton. Eftersom det finns 8,3 megaton reserver och 25 megaton resurser pekade detta resultat på att det inte finns någon större, omedelbar risk för koboltbrist och att den gröna omställningen inte är hotad av detta så länge en del resurser omvandlas till reserver. Vad gäller miljöeffekter så orsakade Scenario I, II och III, utsläpp av 18,0, 15,9 respektive 7,51 kg CO_2-eq/kg kobolt i batterier. Scenario I hade störst miljöpåverkan och Scenario III lägst. Följaktligen, är det mest effektiva sättet att minska kobolts miljöeffekter att förbättra teknologin inom dess livscykel. Detta innefattar, mer specifikt, minskad bränsleanvändning, lägre koboltinnehåll i litiumjonbatterier och att introducera grönare elmixar. Återvinning anses dock fortfarande vara viktig för att kobalts livscykel ska bli hållbar på lång sikt.

Nyckelord

Kobolt, koboltbrist, miljöeffekter, teknologiska framsteg, återvinning

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Abstract

The aim of this study was to investigate future scarcity and environmental effects of cobalt. This was done by creating three scenarios based on different prognoses concerning the future use of cobalt up to the year 2050, *Business as usual* (Scenario I), *Recycling Rate Improvements* (Scenario II) and *Technological Advancements* (Scenario III). Regarding scarcity, Scenario III had the lowest overall cobalt use, 3.68 megatonnes, whilst Scenario I had the highest, 10.8 megatonnes. Comparing this to existing cobalt reserves of 8.3 megatonnes and resources of 25 megatonnes implied that there was no major risk of cobalt scarcity in any scenario and that the green transition is not threatened, as long as some resources are turned into reserves. The opposite relationship was true for environmental impact where Scenario I, II and III had global warming potentials of 18.0, 15.9 and 7.51 kg CO_2-eq/kg cobalt in batteries, respectively. Consequently, the most important action to reduce the environmental effects of cobalt is improving technology which, specifically, involves lowering fuel consumption, reducing cobalt content in LIBs and introducing greener electricity mixes. However, for the cobalt life cycle to be sustainable long-term, improving cobalt recycling is also instrumental.

Keywords

Cobalt, cobalt scarcity, environmental effects, recycling, technological advancements

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cobalt
from German kobalt, alteration of kobold
meaning goblin

Preface/Acknowledgements

This Master's thesis in Environmental Engineering was undertaken at LTH, Lund University at the Division of Environmental and Energy Systems during the spring semester of 2023. The authors were Oscar Gustafsson and Filip Tyberg and both have contributed equally to the report.

We would like to thank André Månberger, associate senior lecturer at the Division of Environmental and Energy Systems, for his valuable contributions and insight in the role as supervisor. We would also like to thank Mikael Lantz, senior lecturer at the Division of Environmental and Energy Systems for his work as examiner. Finally, we would like to extend our gratitude to Cheryl O'Brien, technical information specialist at the US Geological Survey for helping out with image rights for one of the maps featured in this study.

Oscar Gustafsson & Filip Tyberg
Lund, June 2023

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List of Acronyms

AP - Acidification Potential
ASM - Artisanal Small-Scale Mining
BaP-eq - Benzo[a]Pyrene Equivalent (Carcinogenic Potency)
CPL - Concentrated Product Liquor
CTU_e - Comparative Toxic Units (Ecological)
CTU_h - Comparative Toxic Units (Human)
EIA - Environmental Impact Assessment
EIC - Environmental Impact Categories
EtP - Ecotoxicity Potential
EP - Eutrophication Potential
EV - Electric Vehicles
FESS - Flywheel Energy Storage System
FLNC - Front de la Libération Nationale Congolaise/Congolese National Liberation Front
FU - Functional Unit
GHG - Greenhouse Gasses
GWP - Global Warming Potential
HFO - Heavy Fuel Oil
HTP - Human Toxicity Potential
IEA - International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
IRENA - International Renewable Energy Agency
ISO - International Organization for Standardization
LCA - Life Cycle Assessment
LCO - Lithium Cobalt Oxide (Cathodes)
LFP - Lithium Iron Phosphate (Cathodes)
LIB - Lithium-ion Battery
LMO - Lithium Manganese Oxide (Cathodes)
MPR - Mouvement Populaire de la Révolution/Popular Movement of the Revolution
NCA - Lithium Nickel Cobalt Aluminum Oxide (Cathodes)
NMC - Lithium Nickel Manganese Cobalt Oxide (Cathodes)
NMP - N-MethylPyrrolidone
SOC - State of Charge
SSH - Stratiform Sediment-hosted (Deposits)

1 Introduction

When German miners found cobalt in the 16th century they considered the metal to be worthless. It was believed that valuable silver ore had either been stolen, spoiled or replaced with cobalt by mischievous mountain goblins. These mountain goblins were referred to as kobolds which, in fact, is where the name cobalt originates (Merriam-Webster, 2023). But cobalt has not always been considered worthless. Human use of cobalt can actually be traced back to about 3500 years ago to the reign of King Tuthmosis III in the middle of the 18th dynasty of ancient Egypt (Abe et al., 2012). The ancient Egyptians used cobalt as a colorant which, in combination with their advancements in glass production, allowed them to create deep-blue glassware and faïence (Shortland et al., 2006)**.**

Whilst humanity might have found use for cobalt since as far back as in Ancient Egypt, exactly what it has been used for has changed dramatically with time. Today it is mainly found in batteries which power the majority of consumer electronics and electric vehicles (Cobalt Institute, 2022). Because of this cobalt plays a key role in the green transition, which is an important step to counteract and/or mitigate the effects of climate change (Finnish Ministry of the Environment, n.d.). However, there are some problems regarding the future of cobalt. The first problem is the availability of cobalt, as there are indications that cobalt might run out in the, relatively, near future (Zeng et al., 2022a). Furthermore, using cobalt brings with it significant environmental effects associated with mining, processing, battery manufacturing as well as other parts of its life cycle (Farjana et al., 2019). Additionally, much concern has historically been raised on the ethics of cobalt mining, especially in regards to child labor. It is estimated that about 40 000 children work in Congolese cobalt mines which, obviously, is a significant problem. (Zdechovský, 2022) Cobalt could prove crucial in the transition to a greener future but, as there are such significant problems, needs to be studied closely.

1.1 Objectives

In this Master's thesis a thorough examination of cobalt in regard to its scarcity and environmental effects now and in the future was carried out. Scarcity was defined as there not being enough cobalt available, either commercially or physically, to fill demand. The study was based around three future scenarios: Continued and increased use of cobalt based on current usage called *Business as Usual* (Scenario I), improvements in recycling leading to very highly efficient resource recovery compared to current standards called *Recycling Rate Improvements* (Scenario II) and technological improvements leading to more efficient mining and usage of cobalt called *Technological Improvements* (Scenario III). It aimed to better understand potential scarcity and environmental burden of cobalt as well as the impact of uncertainties by answering the following research questions:

- Which scenario has the biggest impact on cobalt scarcity?
- What will each scenario lead to in regards to environmental effects of cobalt supply and demand?

1.2 Delimitations

The study will investigate cobalt from a global perspective. All the world's cobalt resources will be factored in when determining scarcity, although not every single mine will be looked at individually as similar mines will be grouped together. Many different products utilize cobalt but only lithium-ion batteries (LIBs) will be investigated in this report. All life cycle steps, from cradle-to-grave, will be analyzed but with limited focus on the use phase. These steps will individually be divided on geographical terms with at least the three most active countries in each step being investigated. Predictions about future scarcity will be made from today to about 30 years in the future (2050). As recycling will play a large part in this report, especially in Scenario II, cobalt used in LIBs has been divided into two groups, primary cobalt and secondary cobalt. Primary cobalt refers to cobalt extracted from mines, whilst secondary cobalt refers to cobalt coming from recycled LIBs.

A process diagram illustrating the entire life cycle of cobalt based on current numbers and methods is presented below (Figure 1). All calculations and discussions regarding cobalt will be based around this initial process diagram.

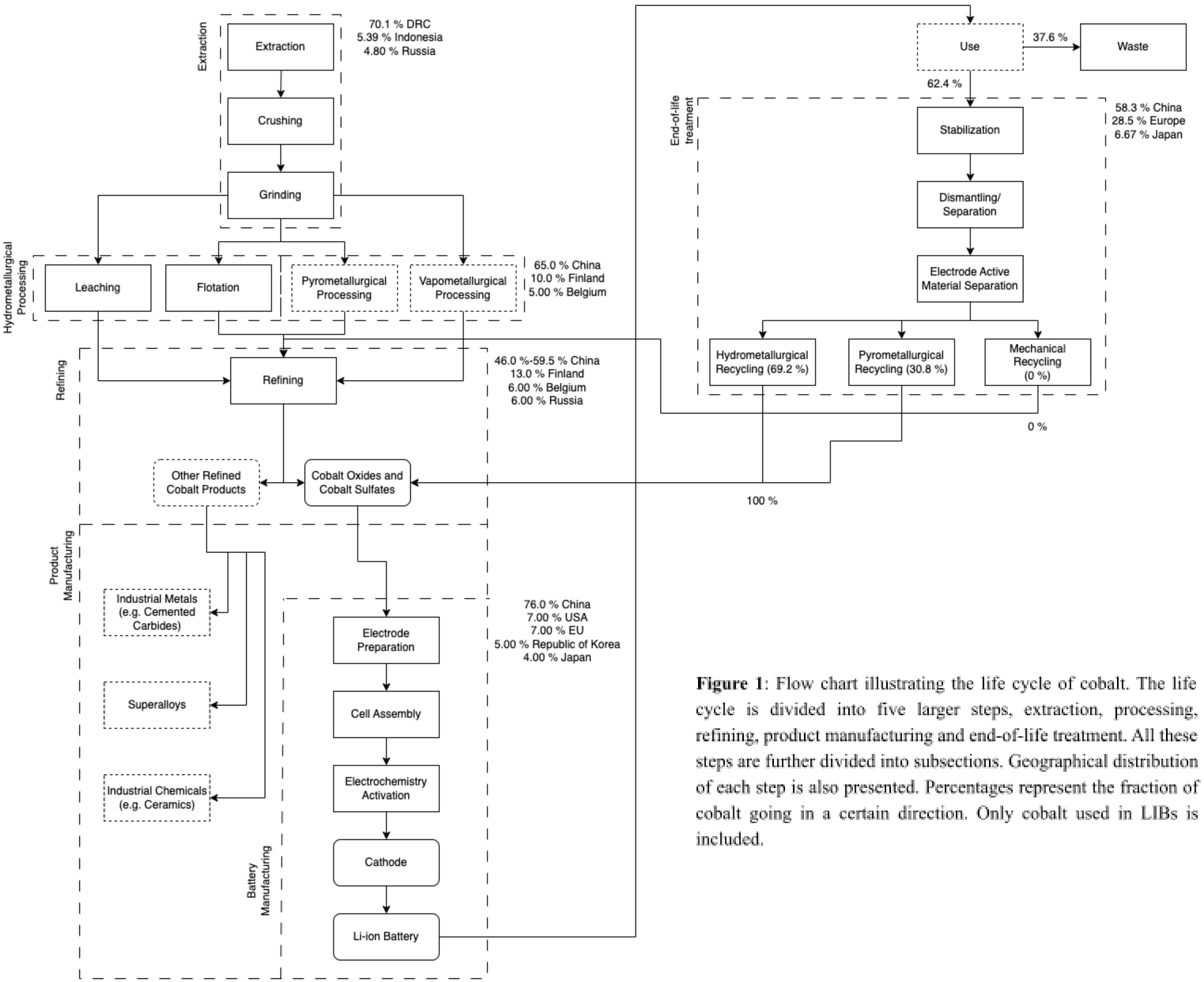


Figure 1: Flow chart illustrating the life cycle of cobalt. The life cycle is divided into five larger steps, extraction, processing, refining, product manufacturing and end-of-life treatment. All these steps are further divided into subsections. Geographical distribution of each step is also presented. Percentages represent the fraction of cobalt going in a certain direction. Only cobalt used in LIBs is included.

2 Methodology

The report was undertaken in the style of a literature study. Data supporting the predictions regarding cobalt scarcity and its environmental effects have consequently been supplied by other scientific studies and surveys. In order to make sure said data is accurate and reliable a comprehensive analysis of each source is carried out. More on data collection is explained in the next section. Calculations were carried out in Google Sheets and Excel, exact descriptions of each calculation as well as with assumptions was presented along with the results and in the Appendices. The environmental impact of cobalt was estimated using an Environmental Impact Analysis (EIA) which in turn was inspired by the structure and methods of a Life Cycle Assessment (LCA). In order to make sure that the environmental impact was allocated towards cobalt, allocation based on mass was carried out. All assumptions used in calculations and graphs are presented continuously in the report.

2.1 Data Collection

Table 1 showcases five example searches along with which search engine was used. These correspond to the approximate amount of search terms that have been used throughout the report. The two primary sources have been Google Scholar and LUBsearch. As can be seen some searches resulted in a very high quantity of results (especially the Google Scholar searches). For these searches only the top results (generally the top 10-50 results) have actually been analyzed and read as these are the most cited and thus, assumed to be, the most relevant. Some searches have also been done by simply using the Google search engine. These results have been thoroughly examined to make sure they are reliable.

Table 1: Overview of the literature search process showing what database, search terms and/or articles were used to find articles later used in the study. Primary search means utilizing the database's search engine and secondary means using the "cited by"-function to find similar articles.

Database	Search Terms or Source Article	Type of Search	Number of Results or Times Cited
Google Scholar	Cobalt Mining	Primary	1 770 000
Scopus	Watari et. al., 2020	Secondary	104
LUBsearch	LCA OR life cycle assessment AND cobalt AND min* OR extrac*	Primary	258
LUBsearch	cobalt AND smelt* NOT waste NOT	Primary	2 294

	recycl* NOT slag NOT leach*		
Google Scholar	lithium ion battery recycling China	Primary	46 400

2.2 Environmental Impact Categories

This study, while not a strict LCA, utilizes some of the methods mentioned in ISO-standard (International Organization for Standardization) 14 044 and will therefore be referred to as LCA-adjacent. In accordance with ISO 14 044:2006 (European Committee for Standardization, 2006), a number of Environmental Impact Categories (EIC) deemed relevant are included in the study. These are: Global Warming Potential (GWP), Ecotoxicity Potential (EtP), Human Toxicity Potential (HTP), Acidification Potential (AP) and Eutrophication Potential (EP).

2.2.1 Functional Unit

As this study is LCA-adjacent, a functional unit of 1 kg of refined cobalt used in LIBs is defined, meaning all EIC will be described based on this metric.

2.2.2 Global Warming Potential

How emissions of greenhouse gasses (GHG) affect the climate is described as Global Warming Potential, which shows their effect on the heat radiation absorption (radiative forcing) of the atmosphere. The GHGs are mainly affecting the radiative forcing positively, i.e. causing a net increase in temperature. A characterization model for GHGs has been produced by the Intergovernmental Panel on Climate Change (IPCC), where the GWP is described in terms of kg carbon dioxide (kg CO_2) per functional unit over a time period of 500 years (Dincer and Bicer, 2018).

2.2.3 Ecotoxicity Potential

The ecotoxicity of a compound or product describes the negative effect it can have on the environment and organisms within the ecosystem. Some examples of affected groups are microorganisms, wildlife and plants. (Rajpoot et al., 2022) Ecotoxicity can be divided into multiple subcategories, for example aquatic and terrestrial, however only aquatic is studied in this report.

Aquatic ecotoxicity refers to the harmful effects on freshwater and marine ecosystems caused by emissions of toxic substances originating from the product investigated, to either the atmosphere, waters and/or soil (Dincer and Bicer, 2018). The severity of the aquatic ecotoxicity is determined by the EtP, which is defined either in kg of 1,4 Dichlorobenzene equivalents (1,4 DB-eq) or, as will be used in this report, Comparative Toxic Units (CTU_e) per functional unit affecting the ecosystem over an infinite amount of time. It aims to describe "... fate, exposure and effects of toxic materials.” (Dincer and Bicer, 2018). The aquatic toxicity is calculated using the model created by USEtox. CTU_e is defined as “...an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted.” (Hauschild et al., 2008; Henderson et al., 2011; Rosenbaum et al., 2011, 2008).

2.2.4 Human Toxicity Potential

In a similar fashion to ecotoxicity, this EIC focuses on the toxic effects released substances have on humans and the human environment. This does, however, not include health risks originating from working conditions in general, but rather focuses on specific toxic effects caused by e.g. processing steps of the functional unit. Just like both types of ecotoxicity, the HTP describes exposure, effects and fate of toxic compounds over an infinite amount of time in terms of 1,4 DB eq or comparative toxic units (CTU_h) per functional unit (Dincer and Bicer, 2018). CTU_h is defined as “... the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue.” or simplified as the disease cases caused per kg of toxic substance emitted. As with ecotoxicity, the HTP is calculated using USEtox (Hauschild et al., 2008; Henderson et al., 2011; Rosenbaum et al., 2011, 2008).

2.2.5 Acidification Potential

The AP describes the acidification of ecosystems, organisms, groundwater, soil, and substances caused by chemical compounds released by different processes related to the functional unit (Dincer and Bicer, 2018). The main compounds responsible for acidification are the gasses sulfur dioxide (SO_2), nitrous oxides (NO_x) and reduced nitrogen (NH_x) and the AP of a compound is measured in amount of SO_2-equivalents per kilogram of product (in this study it corresponds to the functional unit of 1 kg of refined cobalt for batteries) (Farinha et al., 2021). The acidification potential of NO_x corresponds to 70 % of that of SO_2 meaning a conversion factor of 0.7 is used to convert kg of NO_x emissions to kg SO_2-eq (Azapagic et al., 2003).

2.2.6 Eutrophication Potential

Another EIC investigated in this study is the nutrient overload and subsequent undesired species composition change, eutrophication, caused by the release of chemical compounds mainly containing nitrogen and/or phosphorous like ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) (Vallero, 2006) and phosphate (PO_4^{3-}). The degree of eutrophication caused is measured in Eutrophication Potential (EP) and expressed as kilogram phosphate equivalents (kg PO_4^{3-}-eq) per functional unit (Dincer and Bicer, 2018). Like for acidification, the EP for NO_x can be calculated by using a conversion factor. In this case 1 kg of NO_x emissions corresponds to 0.13 kg PO_4^{3-}-eq, i.e. a conversion factor of 0.13 is used (Azapagic et al., 2003).

3 Cobalt Uses

Today the primary use of cobalt is found in cathode material production which is in turn used in rechargeable batteries. Batteries using these cathode materials can range from lithium-ion batteries (which will be the focus of this report) to nickel-cadmium batteries and are, for instance, used in electric vehicles (EV), consumer electronics and electronic tools. The Li-ion batteries can be divided into a number of different cathode chemistries exhibiting different cobalt content and other characteristics (Baum et al., 2022). These cathodes are LCO, LFP, LMO, NCA and NMC, and are discussed in further detail later in the study. Further uses of cobalt can be found in the production of superalloys, alloys with high surface stability used in the turbine engines of jet aircraft, and in cemented carbides, a composite material used in cutting tools made up of cobalt and tungsten carbide. According to data reported in the Cobalt Institute's market report for 2021, about 65 % of all cobalt was used for battery related purposes, 52 % of which (34 % of the total) was used in electric vehicles and 48 % (31 % of the total) in other applications. 14 % of all cobalt usage was classified as industrial metal usage. This mainly encompasses usage in cemented carbides which made up about 37 % of all cobalt industrial metal demand. 11 % of global usage went into industrial chemicals which for instance includes ceramics and dyes (about 28 % of cobalt industrial chemical demand). The final approximate 11 % was used for superalloys (Cobalt Institute, 2022). Comparing this distribution to what it used to look like 27 years ago shows a dramatic shift. Only about 8 % of US cobalt usage went towards battery production in 1996. The majority of cobalt was in fact used for cemented carbides, which covered about 30 % of total usage, and superalloys, which covered about 22 % of total usage (Graedel and Miatto, 2022).

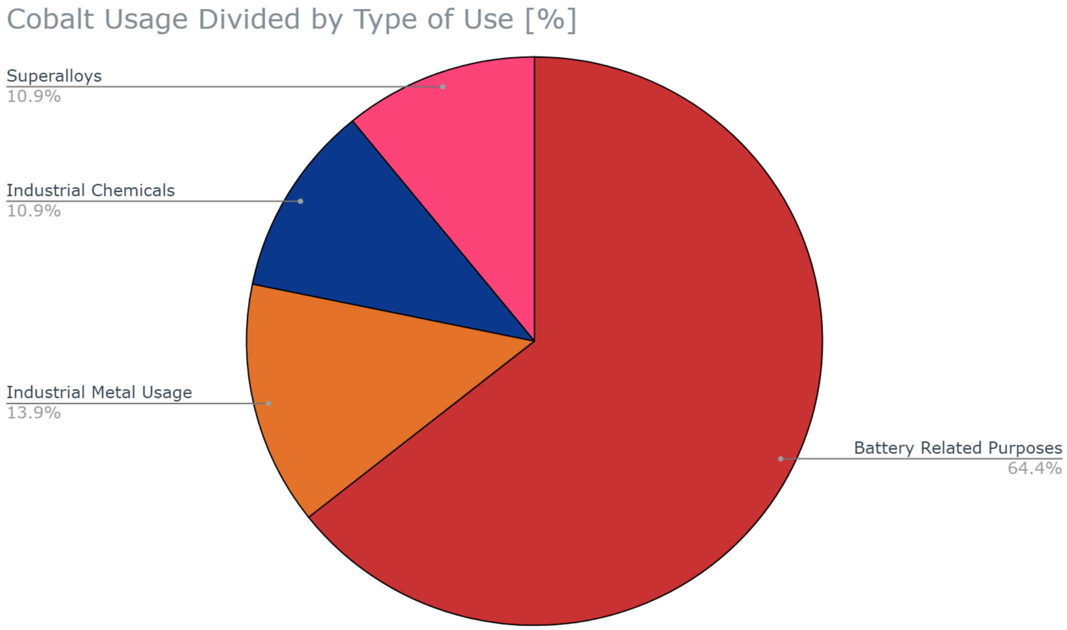


Figure 2: Pie chart showing cobalt usage divided by type of use in 2021 (Cobalt Institute, 2022).

4 Primary Production of Cobalt

For cobalt to enter the global flow of materials and products it first has to be extracted from the ground. This step is known as primary production and will be described in the following section. It will cover the mineralogy of cobalt, i.e. what can be defined as a cobalt deposit, how cobalt is mined, including different methods, and how cobalt ore is treated before entering the processing stage (see Figure 3).

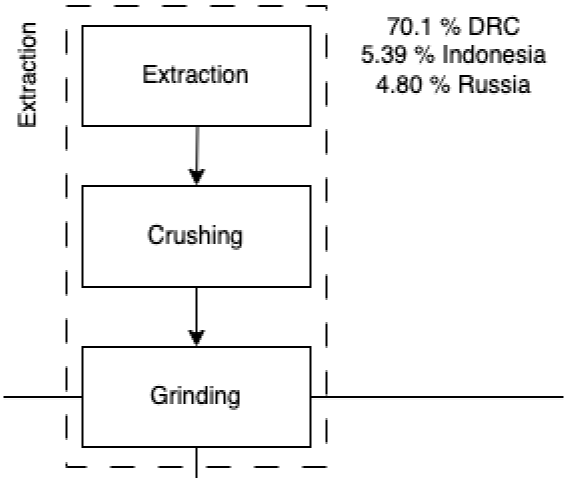


Figure 3: Part of the major flowchart describing the different steps involved in cobalt extraction.

4.1 Reserves vs. Resources

Before going into details concerning the specific mineralogy of cobalt, a definition on how exactly different cobalt deposits should be defined according to the concept of reserves vs resources should be determined. Cobalt reserves can be defined as cobalt quantities that are available, both commercially and geographically. Resources are, contrarily, quantities of cobalt that are not currently available. Resources can be divided into two categories, Contingent resources and Prospective resources. Contingent resources are quantities of cobalt that are known and are, potentially, recoverable but aren't considered economically viable. Prospective resources are not currently known but are counted as accumulations that will be discovered in the future (Ross, 2001).

It should also be mentioned that reserves are not final estimations. What is considered a reserve can change dramatically with changes in social and economic conditions. Higher prices for instance tend to lead to estimates of reserves growing in size whilst lower prices tend to lead to the opposite. With advances in mining technology deposits that once were considered economically unprofitable will become profitable to extract and reserves will thus expand. The same can be said for further exploration and discovery of new deposits. The current reserves presented in this report should therefore not be considered irreproachable (Mudd and Jowitt, 2018).

4.2 Mineralogy of Cobalt

Cobalt is a ferromagnetic metal with atomic number 27 placing it in group 9 in the periodic table. It exists all around the globe but not in any large quantities as it only makes up about 0.001 % of the Earth's crust (The Editors of Encyclopaedia Britannica, 2023). In total, there exists around 25 million tonnes of terrestrial cobalt resources and 8.3 million tonnes of cobalt reserves (U.S. Geological Survey, 2023). Cobalt is deposited differently across the globe, with some deposit types being far more common than others. The most important deposit types are documented in the list below.

1. *Stratiform sediment-hosted (SSH) deposits*, copper-cobalt sulfides in folded shale and dolomite. This deposit type is currently the one with the most abundant reserves available (~14.5 million tonnes) and is thus one of the most important. This type is found in the Katangan copperbelt in the Democratic Republic of the Congo (DRC) and Zambia which are the only countries where cobalt is extracted from sediment-hosted deposits (Figure 4). SSH deposits make up about 47 % of total global reserves and about 75 % of total global production (Dehaine et al., 2021; Mudd et al., 2013; Savinova et al., 2023).
2. *Supergene laterite deposits*, Fe, Ni and Co rich laterite soil profiles formed by surface weathering. This is the second most common deposit type with about ~7.5 million tonnes available. It is common in Cuba, New Caledonia and Cameroon as well as Australia and Russia (Dehaine et al., 2021; Mudd et al., 2013; Savinova et al., 2023).
3. *Magmatic sulfide deposits*, igneous rocks forming Fe-Ni-Co deposits which contain high concentrations of cobalt. Reserves reach about 1.9 million tonnes worldwide. Can be found in Canada, Russia as well as Australia (Dehaine et al., 2021; Mudd et al., 2013; Savinova et al., 2023).
4. *Volcanogenic massive sulfide deposits*, ancient deposits that were formed by submarine hydrothermal processes. Deposits of this type exist in Finland, Canada and China with global reserves being at about 500 thousand tonnes (Dehaine et al., 2021; Mudd et al., 2013; Savinova et al., 2023).
5. *Skarn*, metamorphic or magmatic deposits containing pyrite cobalt ore for example found in Pennsylvania (Mudd et al., 2013).
6. *Vein or replacement deposits*, veins containing large amounts of cobalt (not a mixture of nickel and copper). E.g the Cobalt-Gowganda region in northern Ontario, Canada, which has veins that have reached up to 10 % of cobalt (Mudd et al., 2013).
7. *Submarine deposits*, Fe-Mn-Ni-Cu-Co-Mo deposits found on the seafloor by way of metal precipitation from seawater, can for instance occur at seafloor hydrothermal systems. Crusts form at depths between 800-3000 m and nodules form at depths between 3500-6500 m. Can be found off the coasts of Tonga and the Cook Islands. Exact estimates vary greatly. Some put deposits at only 1.6 million tonnes whilst the US

Geological Survey estimates that deposits reach as high as 120 million tonnes (Savinova et al., 2023; U.S. Geological Survey, 2023).

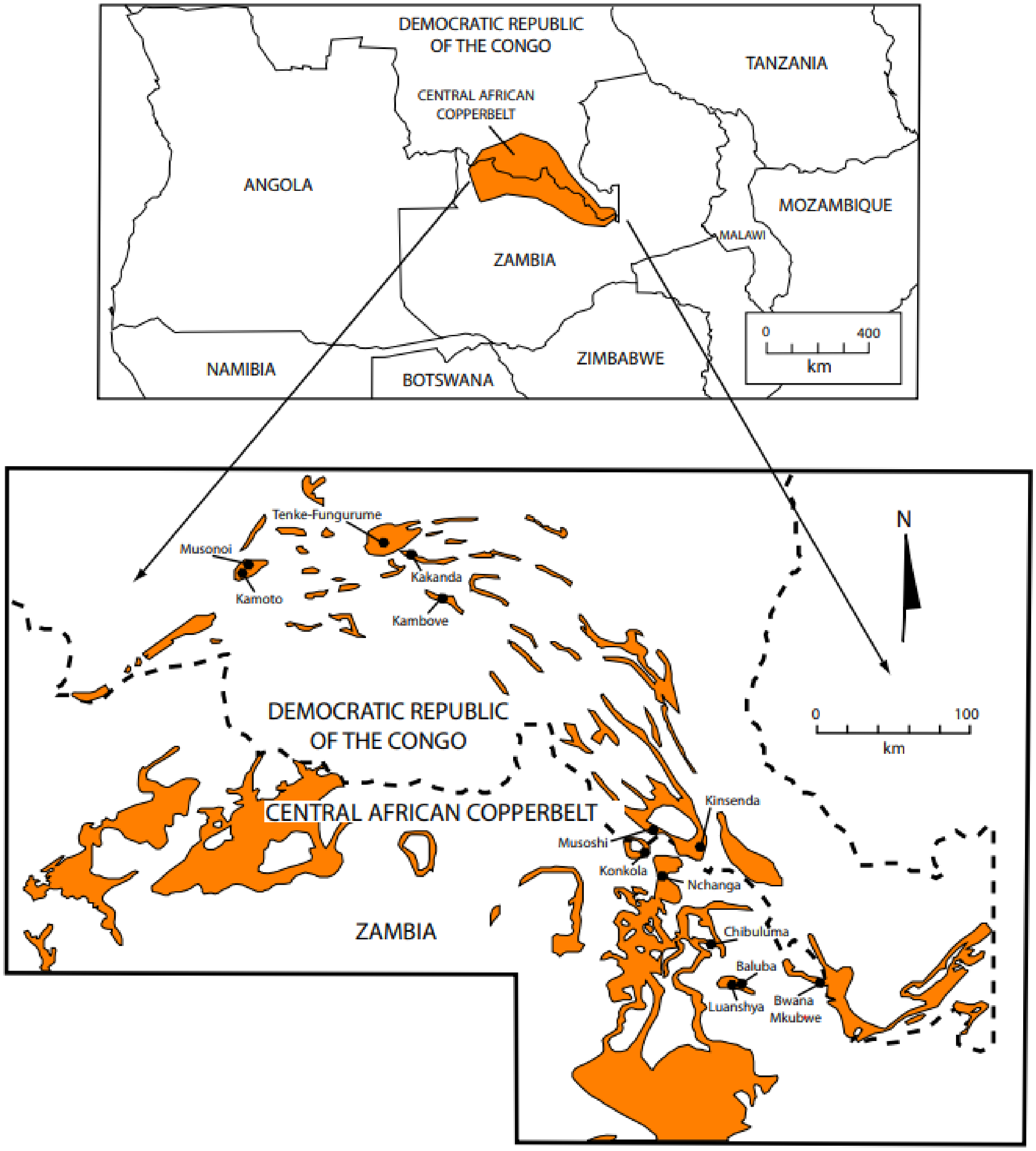


Figure 4: Map over the Katangan copperbelt also known as the Central African Copperbelt (Taylor et al., 2009).

Although cobalt occurrence is more or less limited to the aforementioned deposit types the cobalt-bearing mineral can vary from place to place. The different groups of cobalt minerals extracted as of today are cobalt sulfides (e.g carrollite, cattierite, linnaeite), sulfarsenides (cobaltite), arsenides (skutterudite, smaltite) as well as arsenates (erythrite) and the less exploited cobalt selenides (trogtalite), cobalt oxides (heterogenite, asbolane, lithiophorite) and cobalt carbonates (sphaerocobaltite, kolwezite) (Dehaine et al., 2021).

About 70.1 % of the world's cobalt reserves came from the Democratic Republic of the Congo (DRC) in 2022 meaning that the country contributed about 130 000 tonnes out of the total 185 500 tonnes of cobalt that was produced. Indonesia was the second largest producer with about 10 000 tonnes corresponding to 5.39 % of total production whilst Russia was the third largest producer with about 8 900 tonnes corresponding to 4.80 % of total production. Logically, most of worldwide deposits exist in the DRC as well, with about 4 million tonnes out of the total reserves of 8.30 million tonnes (47.9 %). Second on the list is, however, Australia with 1.5 million tonnes (18.0 %) whilst Indonesia is third with 600 thousand tonnes (7.19 %). The two charts below illustrate the exact geographic distribution of cobalt mining and cobalt deposits (Figure 5 and 6) (U.S. Geological Survey, 2023).

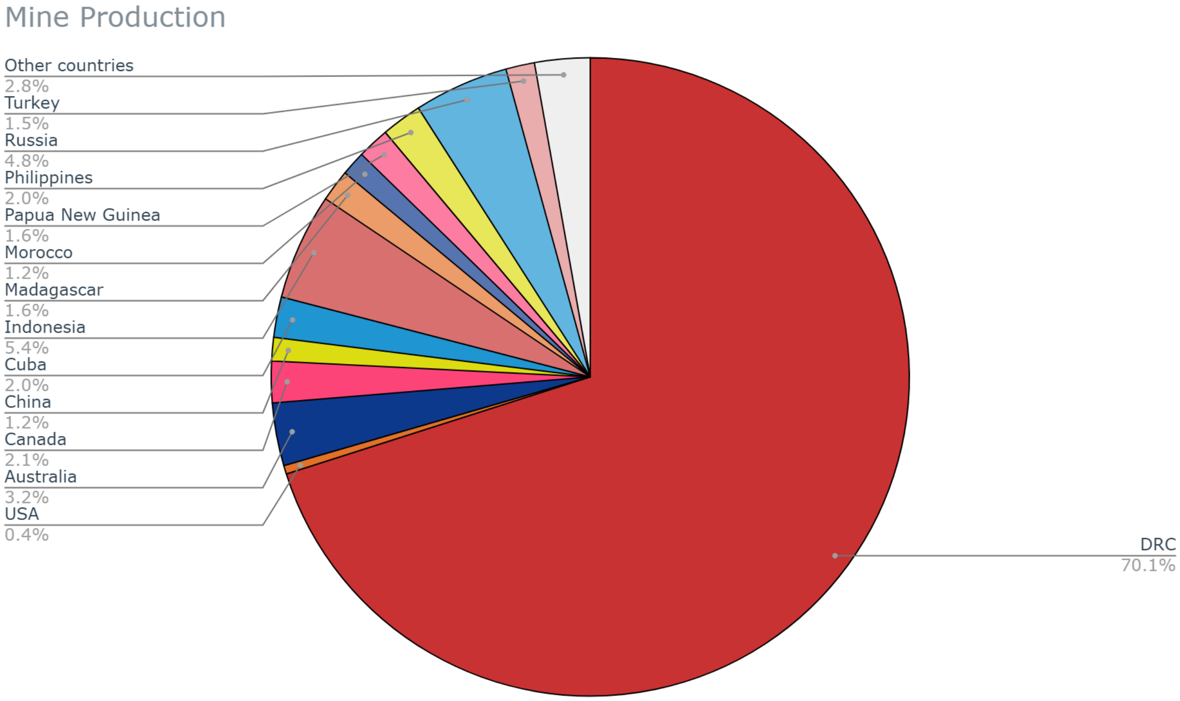


Figure 5: Pie chart showing geographical distribution of mine production in 2022 (U.S. Geological Survey, 2023).

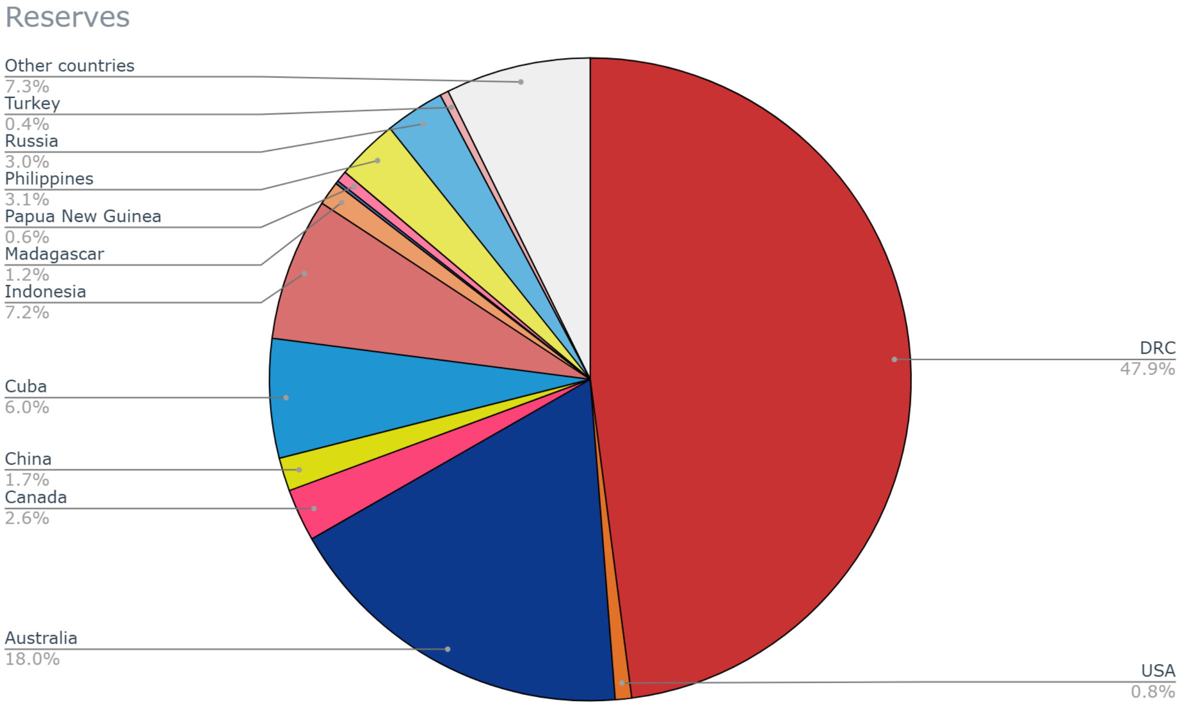


Figure 6: Pie chart showing geographical distribution of reserves in 2022 (U.S. Geological Survey, 2023).

Smith (2001) described cobalt as "Always the bridesmaid, never the bride" which clearly describes cobalt's place in the global economy. When mining, cobalt is almost always seen as a byproduct, with nickel and copper often being the primary target. This indicates that cobalt, on its own, is not a particularly attractive metal from an economic perspective. The extraction of cobalt is also, consequently, highly dependent on the extraction of nickel and copper. If these metals are no longer desired, cobalt will suffer (Mudd et al., 2013).

4.3 Cobalt Mining

There are two main methods in use regarding cobalt mining, open-pit mining and underground mining. Open-pit mining is characterized, as the name implies, by mining directly in an open pit. This is mainly utilized when searching for lower-grade ore located near the surface and is generally low-cost and fast. Underground mining is, in contrast, characterized by mining underground and is used when searching for higher grade ore located deeper underground (Earl et al., 2022). Mining that takes place more than 100 m below the ground is characterized as underground mining (Farjana et al., 2019).

4.3.1 Artisanal Mining

An additional way of extracting cobalt is artisanal mining or, as it is also called, small-scale mining (ASM, Artisanal and Small-Scale Mining). Artisanal mining is, as opposed to open-pit or underground mining, not characterized by where the ore is extracted, but by how it is extracted. ASM utilizes zero to minimal mechanization. It, instead, refers to informal mining performed by individuals, cooperatives, groups or even families. As mechanization is minimal it requires a lot of manual labor and, as it is often informal and unregulated, can be dangerous. This does, however, mean that it is significantly cheaper than traditional mining. ASM brings both positive as well as negative impacts to society. A clear example of this is related to schooling for children. ASM can be a source of income for poor families which consequently would allow them to pay for school fees but, as ASM often involves entire families working together, it can simultaneously pull children out of school (Carstens, 2017; Geological Survey of Sweden (SGU), 2022). Around 25 % of all cobalt extracted globally came from artisanal sources in 2019. For all metals the percentage originating from ASM was about 15-20 % in the same year. This corresponded to about 40 million people being involved in ASM worldwide (Carstens, 2017). The amount of minerals coming from ASM has varied significantly throughout history. Between 1998 and 2006 almost 90 % of all cobalt coming out of the DRC was, for instance, from artisanal sources. This was due to DRC going through a period of civil war and mismanagement of its non-artisanal mines (van den Brink et al., 2020).

4.4 Comminution

After the ore has been extracted from the ground it has to first undergo crushing, followed by grinding. Crushing involves reducing the size of the rock (specifically the particle size of the rock) in order to reach the minerals inside. It generally occurs in two stages, with the first stage utilizing a jaw crusher which reduces the particle size to less than 150 mm. The ore can then be put through a cone crusher which reduces the particle size even further, this time to sizes smaller than 10-15 mm. Following this the crushed material goes through the grinding process. Here it is put through a cylinder mill and the particles are made even smaller (The Editors of Encyclopaedia Britannica, 2006). Following the crushing and grinding processes, the mineral inside the ore has been made much easier to obtain. The physical properties of the ore affects how easily it can either be crushed or ground. Oxide/supergene ores are, for instance, generally easier to both crush and grind than sulfide ores. This means that the most common ore type found in the Katangan copperbelt, *Stratiform sediment-hosted deposits*, which is a sulfide ore, is more difficult to crush than the second most common type, *Supergene laterite deposits* (Mudd et al., 2013; Savinova et al., 2023). Comminution will be said to take place in the same location as cobalt mining in this report.

4.5 Historical Perspective of Supply Shock: The Shaba Crises

Cobalt is not a resource that exists in infinite supply. There may come a time, assuming cobalt keeps getting mined, that it will run out. Most cobalt also comes from the Democratic Republic of the Congo (as was laid out in detail earlier) and is thus highly susceptible to outside factors. If the DRC no longer has the capacity to mine cobalt, global supplies will plummet. Exactly what a world without usable supplies of cobalt will look like is hard to describe but, by taking a lesson from history, can be predicted.

4.5.1 Background

By the year 1977 the Democratic Republic of the Congo, at this point known as Zaïre (a name it had used since 1971 and would use until 1997) had been ruled by Mobuto Sese Seko and his party, the Popular Movement of the Revolution (Mouvement Populaire de la Révolution; MPR) for 12 years (The Editors of Encyclopaedia Britannica, 2023b). The DRC had, since its independence in 1960, gone through many crises and much discord which would lay the groundwork for the so-called Shaba Crises that would plague the country in the upcoming years (Shaba I and Shaba II). The mining province of Katanga (which has been mentioned previously with the focus of the Katanga Copper Belt) was a province that produced much of the world's cobalt and had, in 1960, declared its independence from the country with Moise Tschombe as its leader. This secession was supported by the Belgian government of the time which provided both technical and military covert support. His uprising was also aided by a European-trained mercenary gendarmerie. The secession was brought to an end in 1963 by UN forces (The Editors of Encyclopaedia Britannica, 2023c, 2023d).

4.5.2 Shaba I

On March 8 1977 the Congolese National Liberation Front, or in French, the Front de la Libération Nationale Congolaise (FLNC), invaded Katanga. Katanga was at the time known as Shaba (named after the Swahili word for copper) which is why this period is known as the first Shaba Crisis. The FLNC entered Shaba from Angola with support from the Soviet Union, Cuba, East Germany and Angola. They had a force of 1500 troops under the leadership of one, general Mbumba. Many of those troops were made up of gendarmerie remnants from the 1960 secession. The invasion was successful in the early weeks. Many towns were swiftly captured and rebel forces seemed poised to capture the rich copper-mining town of Kolwezi. What ended up stopping the invasion was foreign aid on the side of Mobutu, with Belgian, French, Egyptian and especially Moroccan troops entering the country. 1500 Moroccan troops airlifted in by French aircraft managed to swiftly retake the towns that had fallen under the control of the FLNC and could thus disperse the rebellion. What drove the first Shaba Crisis was a combination of the failure of Mobutu's regime to achieve any meaningful economic and political growth and, since 1975, failure to stop economic decline, which created dissent among the population, as well as Mobutu's poor relationship with the Angolan government (Ogunbadejo, 1978; The Editors of Encyclopaedia Britannica, 2023e).

4.5.3 Shaba II

What little calm the crushing of the first Shaba invasion had created would prove to quickly dissipate as a second invasion, this time with larger FLNC numbers, would once again come from Angola and strike into the heart of the Shaba province. Shaba II would begin only a year after Shaba I and the FLNC would find more success the second time around. This time they managed to capture Kolwezi and, as a consequence, would incapacitate essentially all of Zaïre's mining output. At the time Zaïre provided around 60 % of the world's cobalt supply, 90 % of which came from Kolwezi (Maidenberg, 1977). The price of cobalt skyrocketed in the first months, going from 6 dollars per pound to as high as 30 dollars per pound. The rebellion was, once again, foiled by foreign involvement, this time with the main actor being France. The French foreign legion would, in the Battle of Kolwezi, retake the city and allow Mobutu to once again reclaim control of the Shaba province. The Shaba crises didn't, in the end, lead to the dethronement of Mobutu but would remain as evidence of the shortcomings of his regime (Young, 1979).

4.5.4 Effects on Cobalt

The global supply of cobalt was undeniably affected by the Shaba crises. With the occupation of Kolwezi by insurgent forces during Shaba II, cobalt production in Shaba ground to a halt causing the price to increase. Zaïre's abundant cobalt supply was one of the main reasons behind the very enthusiastic support Mobutu received from Western sources. At the time cobalt was mostly used for superalloys which consequently made it a very strategic metal, especially for countries with large militaries, a phenomenon especially prevalent during the cold war. Articles published at the time of the Shaba conflict speculated as to how Western powers could react to losing out on Shaba's abundant cobalt supply. If the FLNC separatists were to come out victorious, Zaïre would, most likely, end up as an ally to the Eastern bloc as they were aligned with Angola and received support from both the Soviet Union and Cuba. This could, in a worst case scenario for the Western powers, result in them losing access to the majority of the world's cobalt. One article, published at the time did, however, not think this particularly likely (and was thus proven right) and also claimed that losses could have been offset by substitution with another metal (Young, 1979).

Despite the sudden and temporary stop to cobalt production that occurred with the FNLC's occupation of Shaba, overall cobalt production was actually not affected in any negative way. In fact, cobalt production in Shaba actually increased in the years between 1977 and 1980. What drove the massive price increase was thus not actually caused by any decrease in production but solely fears from the Western bloc that they would potentially lose access to Zaïre's cobalt supply (since the FNLC would align with the Eastern bloc). In 1979 this fear had led global cobalt prices to reach levels 7 times as high as those in 1977 (Gulley, 2022). This price hike changed the way cobalt was used worldwide. Cobalt demand was, in the United States, especially high in 1978 as airplane production was ramping up and drier and catalyst demand was high. As prices increased so dramatically in 1979 demand for cobalt decreased, but, as products still needed to be manufactured, different paths in regard to cobalt usage had to be taken. Nickel-based alloys with higher cobalt content were, for instance, substituted with nickel-base alloys with low or no cobalt content in order to reduce the amount of cobalt these products needed. Additionally, recycling of cobalt in superalloys and cemented carbides was increased which reduced the US' reliance on cobalt import (Sibley, 1979).

Shaba I and II showed how the world could, potentially, react to abrupt changes in cobalt availability. As prices increased so dramatically, companies and countries had to find different solutions to deal with the demand for products that normally would require cobalt. The United States reacted by substituting cobalt, i.e replacing it in products for other metals, and by increasing the recycling of cobalt-containing products, i.e ensuring that less cobalt had to be mined and imported. These are two very logical reactions to cobalt scarcity and it thus seems highly likely that future scarcity would be reacted to in a similar fashion.

5 Processing

Processing, going from ground up ore to unrefined but concentrated cobalt, can either be hydrometallurgical, pyrometallurgical, vapometallurgical or mechanical (or in some cases a combination of several methods), see Figure 7. This step describes these methods and under which circumstances each is used. The choice of which processing method is used depends mainly on the mineralogy of the ore, or more specifically on one main and three other major mineralogical properties. The main property is how oxidized the cobalt-containing ore is and the proportion of cobalt to copper and/or nickel. Of the other major properties the first one is the combined mineralogy of the ore and gangue (medium the desired ore/ores are physically attached to, e.g. quartz), which determines the acid/base consumption for leaching and the efficacy of flotation. The second property relates to the mixture of ores present in the sample and related ease of access to cobalt ore, which controls the susceptibility of the ore to either flotation or leaching. The third property is the purity of the ore and/or ore chunk, which affects the refining step and the quality of the refined product (Dehaine et al., 2021).

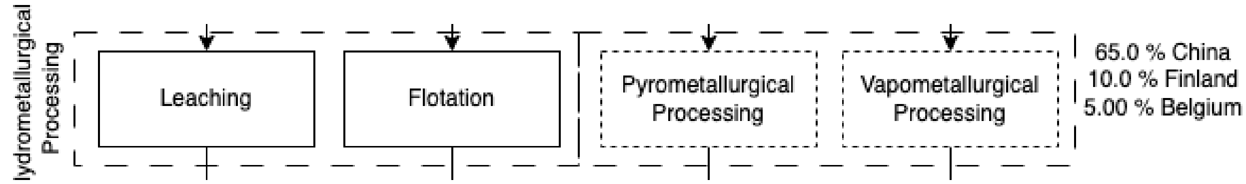


Figure 7: Part of the major flowchart describing the different processes involved in the processing step.

5.1 Hydrometallurgical Processing

Hydrometallurgy is primarily based on the solubility and the electrochemical properties of the cobalt and utilizes leaching and metal recovery to produce the cobalt product. It involves flotation and/or leaching. The flotation separation technique can be used to separate and concentrate the desired mineral from the ore chunk by making the surface hydrophobic via anointing it with a water-repelling substance and letting the ore enter a water tank. This stops the small mineral particles on the surface from coming into contact with water which makes them attach to air bubbles and float to the water surface where a froth containing high concentrations of the wanted mineral is formed and subsequently collected (The Editors of Encyclopaedia Britannica, 2012).

Flotation of cobalt-bearing minerals has, however, gained limited attention as the focus has been on other, main, metals present in the ore. However, for the main cobalt-bearing minerals recovery data has been collected. For carrollite, up to 90 % of the cobalt content has been recovered using flotation. For cobaltite, heterogenite, and a mixture of skutterudite, erythrite and safflorite, the corresponding recovery percentages are 65 %, 95 % and 70 % respectively. The actual recovered amount is naturally very dependent on the deposit type and gangue mineralogy.

In more general terms, more fine-grained minerals, up to a limit, are more well-suited for flotation than coarser ore samples (Dehaine et al., 2021).

The other possible first hydrometallurgical processing step is leaching of the ore. This can either be done using an acid or base to dissolve the desired mineral and subsequently collect the resulting concentrated product liquor (CPL)/pregnant solution. The dissolving agent used depends on the type of ore. For oxides, a solvent of either sulfuric acid or sodium carbonate is used, while sulfates allow the use of either water or sulfuric acid. Regarding sulfide ore deposits, the solvent used is ammonium hydroxide (Santoro et al., 2019). Leaching is conducted according to four different methods: simple leaching, pressure leaching, in-situ leaching, heap leaching or tank leaching (Gill et al., 2023). Focusing on the leachability of cobalt-bearing minerals, the available data is relatively scarce, due to its primary nature as a byproduct. However, some information is known, the primary factor affecting leaching efficiency is, for instance, the mineralogy of the deposit, especially the gangue mineralogy. Additionally, leaching is being used as a cobalt processing step for a number of the major cobalt-bearing minerals despite the information lacuna (Dehaine et al., 2021). Hydrometallurgy does, however, regardless of if flotation or leaching is performed, produce large amounts of acid waste which not only contribute more to its environmental impact but also add additional costs associated with the removal of this acid waste (Earl et al., 2022). More detailed descriptions of flotation and leaching can be found in Appendix A.

5.2 Pyrometallurgical Processing

Pyrometallurgy, on the other hand, is based on the melting points and density of cobalt and other materials present in the ore. It involves chemically removing the cobalt and can be divided into three steps: smelting, chlorination roasting and/or segregation roasting. As with hydrometallurgy, which processing method is used and exactly which steps are involved, is based on properties, such as deposit type, site and composition, of the specific cobalt ore (Earl et al., 2022). Compared to hydrometallurgy, pyrometallurgy is more costly in terms of capital and energy and also produce more emissions and less cobalt ore (as they tend to have lower extraction efficiencies) and is therefore used to a lesser extent in the processing step (Earl et al., 2022; Grimsey et al., 2020). Regarding processing of cobalt ore with the expressed purpose of making batteries, pyrometallurgy is not a viable option as it results in the production of either cobalt metal or cobalt alloy, depending on the involved steps, rather than cobalt oxide/hydroxide (Crundwell et al., 2020).

5.3 Vapometallurgical Processing

Another alternative processing step is vapometallurgical processing. Vapometallurgical processes are used when extracting cobalt from laterite ores. Cobalt ore passes through gasses such as carbon monoxide which vaporizes it, causing the cobalt to be separated from the ore (Farjana et al., 2019). In addition to this, converter matte, a smelted mixture of metals and ore, can also be treated using vapometallurgy to attain purer forms of cobalt from ores (Crundwell et al., 2011a). This is done in a similar manner as with laterite ores using carbon monoxide for vaporization followed by leaching (Crundwell et al., 2011b,). However, like pyrometallurgy, vapometallurgical processing does not make purified cobalt directly viable for LIB production, but rather cobalt metal, and is therefore of lesser interest for this study (Crundwell et al., 2011a).

5.4 Mechanical Processing

An alternative processing method is mechanical separation which is divided into gravity separation and magnetic separation. Gravity separation utilizes the differences in density between desired minerals, gangue and other minerals to separate the desired ore from the rest using contraptions such as shaking tables, jigs and spirals in conjunction. This is an effective separation method for dense cobalt-bearing minerals such as cobalt arsenides or sulfides. It has also been used with success for the sulfarsenide cobaltite but the arsenate erythrite causes cobalt to be lost due to its low density if present during gravity separation. Magnetic separation, as the name implies, rather uses differences in magnetic susceptibility than density of ores to isolate cobalt-bearing minerals from other ores and the gangue. Regarding cobaltiferous minerals, the use of magnetic separation so far has been limited but catterite, lithophorite and erythrite have all been successfully isolated by utilizing their paramagnetism (Dehaine et al., 2021). Due to the relatively limited use of both methods, mechanical processing is not of direct relevance to this study.

5.5 Geographical Distribution of Processing

Processing, according to data from the International Energy Agency (IEA) occurs mainly in China, with about 65 % of worldwide processing taking place there in 2019. The next two biggest processing countries are Finland and Belgium which process 10 % and 5 % respectively (IEA, 2022a).

6 Refining

After the cobalt has been extracted and processed it has to undergo a refining stage which means that impurities are removed from the cobalt. The refining step can be seen in Figure 8. This process will be laid out in detail in Appendix B and will use the Yabulu Nickel Refinery in Australia as an example. In short, CPL is refined and turned into cobalt oxides which can be used for battery manufacturing. The process additionally leads to the formation of ammonia which must be treated (Fittock, 1992).

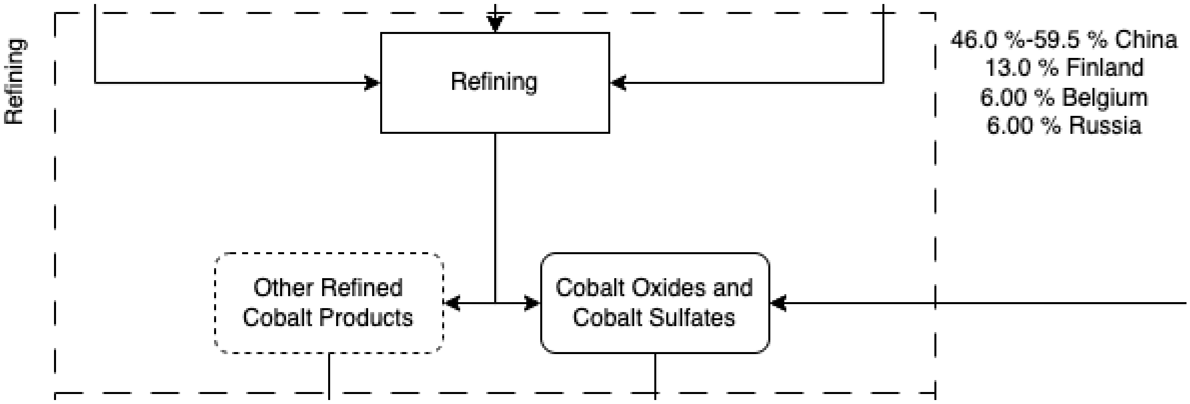


Figure 8: Part of the major flowchart describing the different processes involved in the refining step.

6.1 Geographical Distribution of Refining

The majority of worldwide cobalt refining occurs, as with processing, in China. About 46-60 % of all refining occurred in China in 2016 (van den Brink et al., 2020; Zhang et al., 2021). Finland refined the second highest volume of cobalt the same year, contributing about 13 %, whilst Canada and Belgium were tied for third with 6 % each. 5 % of all refined supply also came from Zambia. Processing and refining will be assumed to occur in the same location in this report (as in the Yabulu refinery). There will thus be no transport between these two stages. The global distribution is very similar, with China dominating (with values only differing by about 5-10 %), Finland processing and refining the second most (only differing by 3 %) and Belgium being third (only differing by 1 %). The only major difference was that Canada refined as much as Belgium. The report will, however, use data for the processing stage as two different values related to refining distribution were found. It was consequently concluded that there was enough uncertainty related to these values for them to be disregarded.

7 Battery Manufacturing

Cobalt can, as was previously mentioned, be utilized in many different ways. In this study, however, only cobalt that is used in battery production will be investigated (IEA, 2022b). The manufacturing of LIBs goes through twelve steps: slurry mixing, coating, drying, calendering, slitting, vacuum drying, jelly roll fabrication/stacking (different process depending on the type of battery cell: pouch cells use stacking and both cylindrical and prismatic cells use winding), welding, enclosing, formation, and aging. For simplification the process can instead be divided into three main steps: electrode preparation (slurry mixing, coating, drying and solvent recovery), cell assembly (calendering, slitting, vacuum drying and stacking) and electrochemistry activation (welding, enclosing, formation, and aging), see Figure 9 (Liu et al., 2021). This chapter will describe these manufacturing processes as well as specifics for the major Li-ion cathodes (where the cobalt is found) like lifetime and cobalt content.

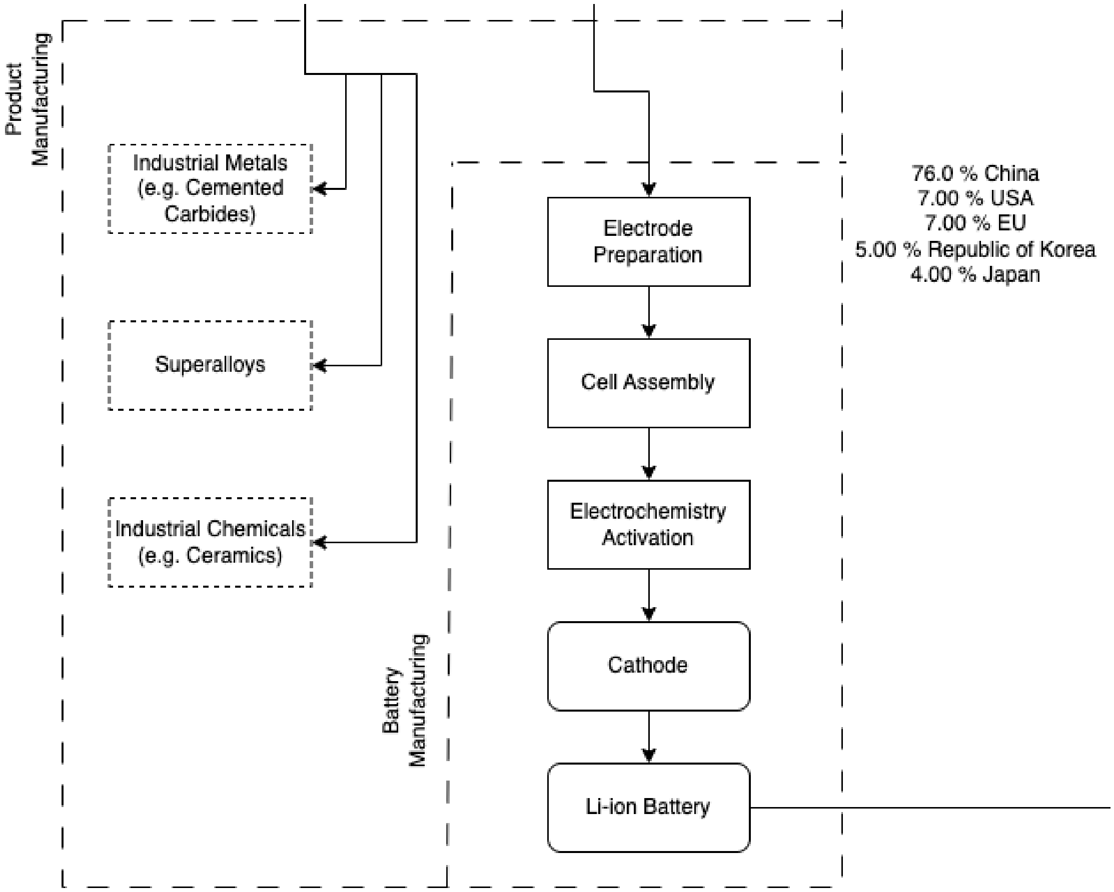


Figure 9: Part of the major flowchart describing the different processes involved in the product manufacturing step.

7.1 Electrode preparation

The electrode preparation is initiated by mixing the active material (Goodenough, 2013), e.g. lithium cobalt oxide for the cathode and graphite for the anode (Barbosa et al., 2021) with solvent, a conductive additive and binder creating a slurry. The chemicals used in this step differ between the cathode (the positive electrode/pole of the battery) and the anode (the negative electrode/pole of the battery) (Schumm, 2023). The cathode slurry commonly utilizes N-methyl pyrrolidone, which is toxic and therefore heavily regulated, to dissolve polyvinylidene fluoride (the binder), while the anode slurry is manufactured by dissolving styrene-butadiene rubber (binder) in water with carboxymethyl cellulose. Following this, the slurries are pumped into trays where they are coated in metal foil, aluminum for the cathode and copper for the anode. Subsequently, the coated cathode/anode is brought to the drying stage where the solvent is evaporated. As N-methyl pyrrolidone is hazardous to the environment, the cathode solvent is recovered during drying to avoid emissions leaving the facility, albeit at a 1 % loss (Sliz et al., 2022), while the anode solvent is deemed nontoxic and released directly into the environment. The solvent recovery step uses 10 kWh of electricity to evaporate and recover the N-methyl pyrrolidone which corresponds to about 420 kWh for a 10 kWh LIB (Ahmed et al., 2016).

7.2 Cell Assembly

The next step, cell assembly, begins with calendering, compression and smoothing of a sheet material using two heated rolls to apply pressure (The Editors of Encyclopaedia Britannica, 2007a), to assist in the enhancement of physical properties of the electrodes such as bonding, conductivity, density or porosity. After the calendering the electrodes are nearly ready to be incorporated into a battery cell and are thus stamped and slitted to the correct size for the cell. They are then vacuum dried to eliminate remaining traces of water. After the electrodes are dry they are kept in dry conditions and sent to a dry chamber where they are either stacked or winded (depending on final cell type) in layers with dried separators between to build up internal cell structure (Liu et al., 2021).

7.3 Electrochemistry Activation

Following cell assembly is electrochemistry activation, where copper and aluminum sheets are welded onto the anode and cathode of the dried and stacked/winded cells respectively. This is mostly done with ultrasonic welding but resistance welding is also used in some cases. The cell stack is then enclosed in the dedicated outer “shell” (the casing of a car battery) which is filled with electrolyte before final enclosure. The dimensions of the casing are not standardized and therefore the size of batteries differ to some degree between manufacturers. Finally, before the batteries are sent to be used, they are subjected to formation and aging beginning with charging of the battery at a low voltage, e.g. 1.5 V, to protect the copper sheet from corrosion. After resting and electrolyte wetting, the battery cells are subjected to slow charge and discharge with charge/discharge rate increasing with time, forming a stable solid-electrolyte interface layer to hinder electrolyte loss and protect the anode from overpotential (caused by fast charging). This process produces gas that needs to be discharged for hazard avoidance. The final major step, aging, is then initialized, which simply consists of leaving the cells on shelves under suitable conditions to allow the finalization of electrolyte wetting and stabilization of the stable solid-electrolyte interface layer. The aging step often takes multiple weeks, followed by a degassing and then a final sealing (Liu et al., 2021). The energy consumption per battery cell can be seen in Table 2 below.

Table 2: The energy consumption per battery cell and step of battery manufacturing as well as processing time and percentage of total energy consumption. Based on (Liu et al., 2021).

Manufacturing Processes	Energy Consumption [kWh/cell]	Percentage [%]
Slurry Mixing	0.11	0.83
Coating	0.18	1.36
Drying/Solvent Recovery	6.22	46.84
Calendering	0.38	2.86
Slitting	0.71	5.35
Stacking	0.77	5.80
Welding	0.25	1.88
Enclosing	0.69	5.20
Formation/Aging	0.07	0.53
Dry Room	3.9	29.37

7.4 Cathodes

There are three main groups of cobalt compounds received in the refining step that are subsequently used in the battery manufacturing process: metallic cobalt, cobalt oxides and cobalt sulfates (Jankovský et al., 2016; Orman and Wiseman, 1984; PubChem, 2023). Metallic cobalt is however not looked at in this study. Depending on the form of cobalt, different methods are used to produce the active material of batteries. As mentioned earlier, the part of the battery where the cobalt is used is the active material of the cathode (Barbosa et al., 2021). There are five main cathodes utilized in LIBs: LCO, NMC, LMO, LFP and NCA (Baum et al., 2022). How each cathode is produced can be found in Appendix C.

7.4.1 Lithium Cobalt Oxide Cathodes (LCO)

LCO cathodes, which are a type of layered cathodes, consist of lithium cobalt oxide ($LiCoO_2$) (Baum et al., 2022). The large difference in both size and charge between Li^+- and Co^{3+}-ions means that the $LiCoO_2$ cathode has a good cation ordering, leading to good values for electrical conductivity. This, along with the well-defined structural stability of layered cathodes, allows for rapid charge/discharge of the battery as well as good conditions for recharging with minimum functional losses. These characteristics are the primary reasons for the lithium cobalt oxide cathode's role as one of the best performing LIB cathodes at the time of writing. The LCO cathode does however have a practical limit of a current flow of around 140 mAh/g (Manthiram, 2020). It is also worth noting that LCO cathodes have some concerns regarding their lifetime and safety (Månberger and Stenqvist, 2018), which leads to LCOs not being used in electric vehicles but rather in consumer electronics like smartphones where the high energy density is desired (Ding et al., 2019). The cobalt content of lithium cobalt oxide cathodes span between 17 to 20 % (Melin, 2019) and the market share of LCO cathodes as of 2016 is 21 % (Zeng et al., 2022b).

7.4.2 Lithium Nickel Manganese Cobalt Oxide Cathodes (NMC)

The other, major, type of layered cathode is the NMC cathode which uses some form of lithium nickel manganese cobalt oxide ($LiNi_{1-y-z}Mn_yCo_zO_2$) as active material. The NMC cathode has become an alternative to LCO due to the aforementioned current limit and high cost of $LiCoO_2$ leading to partial substitution of cobalt with manganese and/or nickel. The advantages of Mn compared to Co is the substantially higher abundance and chemical stability of manganese as well as lower negative environmental impact. Cobalt excels in structural stability and electrical conductivity, while nickel is an intermediate between the other two transition metals. Because of this, Co is progressively exchanged for Ni in NMC cathodes to decrease costs and keep a relatively high structural stability. (Manthiram, 2020) The cobalt content of a standard NMC cathode is around 20.4 % depending on how much of it is substituted for Ni/Mn (Melin, 2019). The metal composition of different NMC cathodes are denoted as NMCxyz e.g. NMC111 which has the chemical composition $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$. Other notable examples are NMC523, NMC442, NMC622 and NMC811 (Gourley et al., 2020; Månberger and Stenqvist, 2018; Melin, 2019). The market share of NMC cathodes is 26 % (Zeng et al., 2022b).

7.4.3 Lithium Manganese Oxide Cathodes (LMO)

Another type of cathodes are LMO cathodes which generally do not contain cobalt, but rather opt for lithium manganese oxide ($LiMn_2O_4$) as active material. Due to the overall lack of cobalt and smaller market share (8 % (Zeng et al., 2022b)) the LMO cathodes are of minor importance for this study. Due to bad reliability the use of LMO cathodes is limited to niche applications (Gourley et al., 2020).

7.4.4 Lithium Iron Phosphate Cathodes (LFP)

One cathode that is important despite its general lack of cobalt content is the LFP ($LiFePO_4$) cathode due to its importance in the electric vehicle industry. It is a type of polyanion cathode consisting of lithium iron phosphate as active material (Darbar et al., 2022). LFP cathodes are more complex than e.g. LCO or LMO ones, but come with the advantages of higher operating voltage, thermal stability and improved safety (Manthiram, 2020). LFP cathodes specifically exhibit these characteristics as well as low production cost and a relatively high capacity of 160 -

170 mAh/g (Darbar et al., 2022). LFP cathodes have a relatively long lifetime and low cost, but lower energy density than other cathodes (Ryu et al., 2021). LFP cathodes currently hold the largest market share of cathode materials at 36 % (Zeng et al., 2022b).

7.4.5 Lithium Nickel Cobalt Aluminum Oxide Cathodes (NCA)

The final major cathode type is the NCA cathode, generally consisting of lithium nickel cobalt aluminum oxide ($LiNi_{1-x-y}Co_xAl_yO_2$) as active material (Li et al., 2020). It is similar to the NMC cathode but has substituted the manganese ion with an aluminum ion for longer life time and increased specific energy. This does, however, not affect other performance factors noticeably as both NCA and NMC run at about 3.7 V with a capacity of circa 200 mAh/g. The main advantages of the NCA cathode are as mentioned, while the disadvantages consist of high costs and low safety level (Liu et al., 2018). It also features a relatively low cobalt content of 2.9 % and holds a market share of 9 % (Melin, 2019; Zeng et al., 2022b).

7.4.6 Cathode Summary

Table 3 summarizes the cobalt content and market shares of all five cathodes.

Table 3: Cobalt content and market shares of LCO, NMC, LMO, LFP and NCA cathodes.

Cathode	Cobalt Content [%]	Market Share [%]
LCO	17-20	21
NMC	20.4	26
LMO	0	8
LFP	0	36
NCA	2.9	9

7.5 LIB Lifetimes

The lifetime of a battery differs greatly with its application. Some applications cause quicker degradation of the battery whilst others allow it to last longer. There is therefore no singular value for how long a specific type of battery is expected to last. According to one article, cobalt-containing batteries in electric vehicles tend to, on average, last about 8 years whilst they last about 7 years in electric buses and 10 years in energy storage systems (Zeng et al., 2022a). Another report authored by the Pacific Northwest National Laboratory in 2019 put the average lifetime of, specifically, lithium-ion batteries at about 10 years (Mongird et al., 2019), although this data does not specify how the LIBs are used. In addition to this, the lifetime of the five LIB cathodes were found to be 2.5-5 years (LCO, converted from cycles to years) (Spitthoff et al., 2020), 8-12/10+ years (LFP, depending on anode), 6-10 years (LMO), 8-10 years (NCA), and 8-10 years (NCM) (Porzio and Scown, 2021). With all the above values in mind this report assumed the lifetime of the average, current, LIB to be 10 years which was used throughout the study.

7.6 Geographical Distribution of Battery Manufacturing

Battery manufacturing is as with previous steps, dominated by China, with about 76 % of global battery production occurring there in 2021. Following China about 7 % of global battery production occurs in the United States and the European Union separately, with an additional 5 % coming from the Republic of Korea and 4 % coming from Japan (IEA, 2022b).

8 Recycling

Lithium-ion batteries (LIB) are not easily recycled. They, as compared to for instance a lead battery, are very compact and not dismantled easily. Cathodes, separators and anodes are tightly packed in the battery cell via folding, winding and stacking. The cells are then put together creating a module which is subsequently assembled into a pack (with additional circuitry). There are many different ways of recycling a Li-ion battery with different methods being more suitable for different battery types and volumes. LIB recycling is based on similar concepts as cobalt processing with both pyrometallurgical recycling and hydrometallurgical processing being in use (Figure 10) (Gaines et al., 2018). Around 4.68 MJ are required to recycle 1 kg of LIB cells in pyrometallurgical processes whilst 0.125 MJ are required in hydrometallurgical processes (Samarukha, 2020).

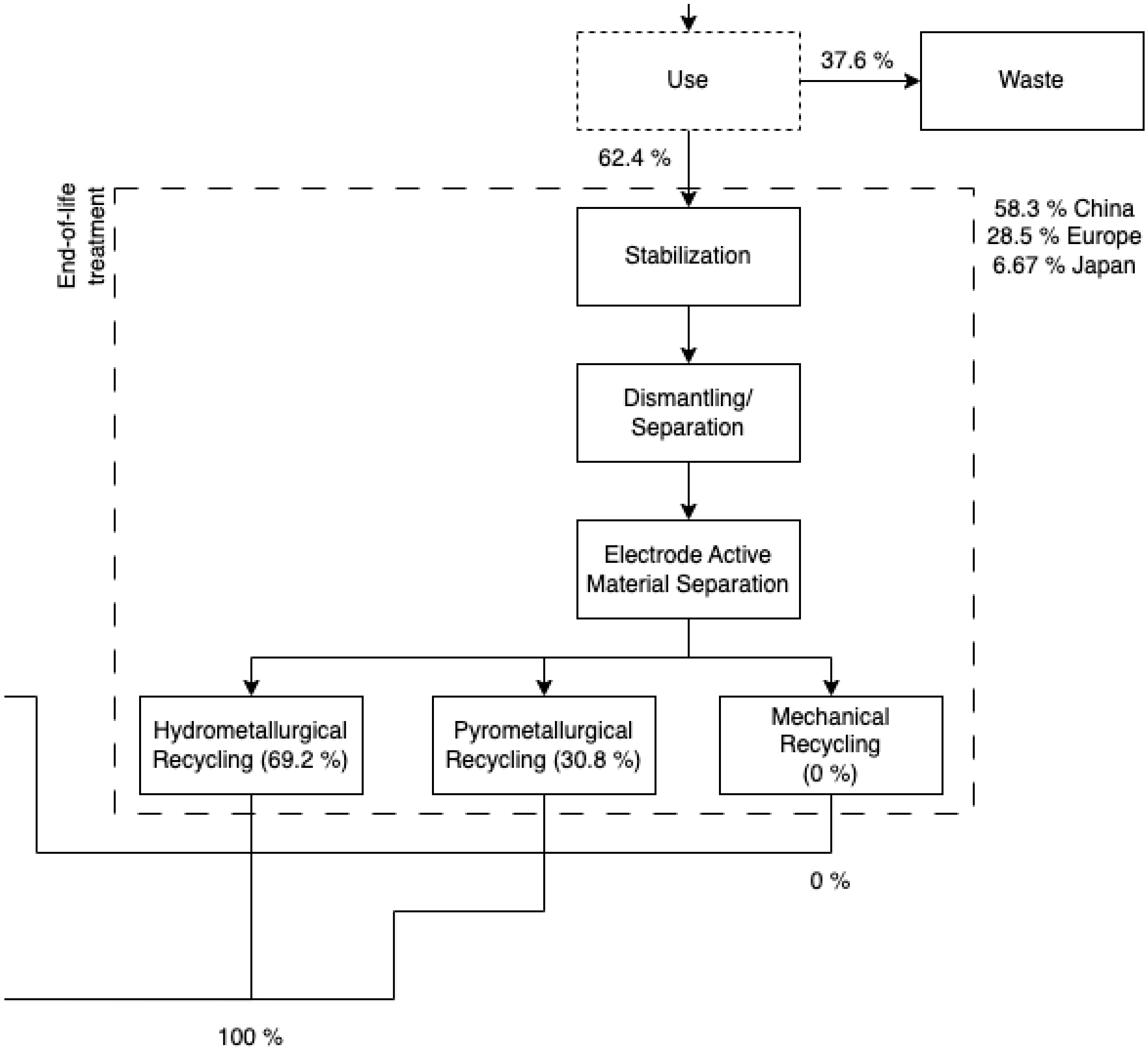


Figure 10: Part of the major flowchart describing the different processes involved in the end-of-life step.

8.1 Pretreatment

Before an LIB is recycled it has to undergo pretreatment. Pretreatment of LIBs is divided into three different stages, stabilization, dismantling/separation and electrode active material separation. Stabilization means that the battery is, as the name implies, stabilized. This is done due to risks connected with residual power in the battery. Dismantling/separation simply involves separating and collecting cathode materials in a manual or mechanical process and electrode active separation collects active materials via a chemical or physical process. A more in depth description of each stage can be found in the Appendix D (Wu et al., 2022).

8.2 Pyrometallurgical Recycling

Pyrometallurgical recycling is based on smelting and is mainly useful when recovering transition metals, such as cobalt and copper (Cotton, 2023), from the battery. It has an advantage in that many different types of batteries can be recycled the same way, with it being less restricted by cathode composition than other recycling processes. It is an expensive process as, among other things, treatment is needed to prevent harmful organics and fluorines from being released. Another issue with pyrometallurgical recycling is that it doesn't naturally separate out cobalt (or nickel). Cobalt has to be removed by leaching which, as cobalt is a highly sought after metal, is necessary for LIB recycling to be profitable (Earl et al., 2022; Gaines et al., 2018). Generally, in the LIB recycling industry, pyrometallurgical processes are mostly used in products with high cobalt content (Wu et al., 2022).

Pyrometallurgical recycling is primarily done in three different ways, direct roasting, in situ reduction roasting and salt roasting. Direct roasting utilizes temperatures above 1000 °C to reduce metal oxides into alloys. Metal materials can then be recovered from these alloys. It consists of first calcining spent LIBs in a furnace (with temperatures above 1000 °C), then adding slag-forming agents (for instance Al2O3 or SiO2) into the furnace with the intention of separating alloys from slags. An issue with this process is that many valuable materials remain in the slag like aluminum, manganese and especially lithium (but not cobalt). These are generally wasted in the process although some techniques have been developed to recover lithium. Direct roasting has additional problems like requiring a lot of energy and causing environmental pollution (Wu et al., 2022).

In situ reduction roasting differs from direct roasting in that it is performed under either a vacuum or an inert atmosphere and that it utilizes pyrolysis. By performing roasting in this manner, the conversion temperature of the cathode materials is reduced, the entire procedure is simplified and the cost of recovering metals is lowered. In situ reduction roasting of LIBs has been shown to be able to recover cobalt. This method has been shown to be able to recover significant amounts of cobalt from LIBs, one experiment for instance managed to recover 99.1 %

of cobalt from a spent NMC cathode by utilizing in situ reduction roasting. In situ reduction roasting can, however, release exhaust gasses that require secondary treatment (Wu et al., 2022).

Salt roasting utilizes, as the name suggests, salts in order to reduce the roasting temperature and increase the metal recovery rate. Some methods based on this process are chlorination roasting, nitration roasting and sulfation roasting. There are several advantages of doing this, salts are for instance relatively environmentally friendly and the process is simple and low cost. Waste is also reduced by utilizing salt roasting as it increases recovery efficiency. This is especially true for lithium recovery. Salt roasting is based on the fact that the crystal structure of cathode is much easier to destroy when in a high salt environment, allowing lower temperatures to be used. It does, like in situ reduction, also produce toxic gasses (e.g. Cl2, NO_x or SO_x) which will have to be treated (Wu et al., 2022).

8.3 Hydrometallurgical Recycling

Hydrometallurgical recycling is based on the same principles as hydrometallurgical processing, i.e. aqueous chemical treatment of Lithium-ion batteries (leaching). Hydrometallurgy requires lower temperatures and investments. It also, compared to pyrometallurgical processes, requires less energy, recovers a higher degree of LIB components, produces less CO_2 emissions and, finally, recovers products with higher purity (Wu et al., 2022). The cathode is exposed to acid in order to separate its components from each other. The more acidic the solution, the more separation is possible. Hydrometallurgy has the benefit of separating the lithium from the transition metals and, subsequently, of being able to separate the transition metals via solvent extraction. It does so by, instead of utilizing solvent extraction, making use of precipitation in order to extract transition metals which can be reused in a new cathode (Earl et al., 2022; Gaines et al., 2018). Hydrometallurgy does also have some downsides. It, for instance, requires sorting and separation in order to recover specific metals, like cobalt, nickel, aluminum, copper and manganese, which can be difficult. The leaching process also produces wastewater which has to be treated. This adds an additional cost to the recycling process (Wu et al., 2022).

There are multiple ways of performing hydrometallurgical leaching. Similar to hydrometallurgical processing, both base leaching (or alkali leaching) and acid leaching are options. Additional ways are bioleaching and special solvent leaching. All these leaching methods are based on the concept that metals (like lithium, cobalt, nickel etc.) dissolve from spent LIBs when those LIBs are put in a solution. The type of solution then depends on which type of leaching is used. Base leaching uses basic solvents, most commonly ammonia (NH_3), and a reducing agent. Acid leaching naturally uses acids, for instance HCl, H_2SO_4 or HNO_3. Both base and acid leaching are quite low cost whilst base leaching is more selective than acid leaching and acid leaching is more efficient than base leaching. Bioleaching is more environmentally friendly than acid and base leaching as it uses inorganic acids (e.g H_2SO_4) produced by bacteria and organic acids (e.g citric acid, $C_6H_8O_7$) produced by fungi. It, however, takes a long time for the microbes to cultivate, the efficiency is relatively low and the operation is susceptible to contamination (Wu et al., 2022).

Following the leaching step, the recycling product is further separated and purified. This is primarily done via either solvent extraction or chemical precipitation. Solvent extraction is a process that utilizes extractants like bis(2,4,4-trimethylpentyl) phosphinic acid (Cyanex272) or bis-(2-ethylhexyl) phosphoric acid (D2EHPA) in order to extract valuable metal ions (Li^+, Co^{2+}, Mn^{2+} or Ni^{2+}). If separation and purification is done via chemical precipitation the products are instead put in a solution that, through pH adjustment, causes impurities to be removed. Al, Cu and Fe precipitate at low pH and are thus removed first whilst Li, Co, Ni and Mn require further processing to be recovered (Wu et al., 2022).

8.4 Mechanical Recycling

A third way to recycle LIBs that is used to a far lesser extent than the previous two is direct, mechanical recycling. These types of processes utilize cutting and separating in order to recycle the battery, skipping hydrometallurgical steps like leaching and pyrometallurgical steps like thermal treatment. One mechanical recycling process in use is the Akkuser process (used in Finland) (Velázquez-Martínez et al., 2019).

8.5 Recycling End Products

The end product of LIB recycling differs depending on which methods are in use and what the goal of the recycler is. Some produce cobalt in the form of an alloy or as cobalt oxide, which thus allows for different uses of the recycled cobalt. Others produce recycled cathodes in their entirety or other products used in the manufacturing process, thus being of use further down the chain of production. Several established recycling technologies are presented in Table 4 below along with their end products. The capacity of each of these processes is based on data from 2019. Only processes capable of producing cobalt-related end products will be discussed. This means that established LIB recycling processes such as Toxco/Retriev and Accurec which primarily produce Li_2CO_3 will not be discussed. A more in depth description of each process can be found in the Appendix D.

Table 4: Processing method, capacity, market share and end product of the main LIB recycling processes.

Name of Process	Processing Method	Capacity in Tonnes of LIBs Per Year (2019)	Market Share (2019)	End Product
Sumitomo-Sony[a]	Pyrometallurgy	150	0.223 %	CoO

Recupyl Valibat[a,b]	Hydrometallurgy	110	0.157 %	$LiCoO_2$ or Co
Umicore Valéas[a,b]	Pyrometallurgical/ Hydrometallurgical	12 000	17.1 %	$LiCoO_2$
Inmetco[a,b]	Pyrometallurgical	6 000	8.54 %	Co Alloy
Glencore[c]	Pyrometallurgical	7 000	9.96 %	Refined Co
JX Nippon Mining and Metals[b,c,d]	Pyrometallurgical/ Hydrometallurgical	5 000	7.11 %	Refined Co
GEM High-Tech Co.[b,e]	Hydrometallurgical	30 000	42.7 %	CoO or Cathode Materials
Brunp Co.[b,f]	Hydrometallurgical	10 000	14.2 %	CoO or Cathode Materials

[a] (Velázquez-Martínez et al., 2019)
[b] (Pinegar and Smith, 2019)
[c] (Makuza et al., 2021)
[d] (Botelho Junior et al., 2021))
[e] (GEM Co., Ltd., 2021)
[f] (Brunp Co. Recycling, 2023)

The recycling processes in Table 4 are either hydrometallurgical or pyrometallurgical (thus no mechanical recycling). The processes covered a capacity of 70 260 tonnes of LIBs per year. This is less than the total global capacity today (see next chapter). The data will not, however, be used to get an idea of how much recycling takes place in total (as the data was from 2019). From these numbers, a percentage of how much recycling is done via pyrometallurgical or hydrometallurgical means can be calculated. These values are approximate but the results were as follows. Pyrometallurgical recycling is used in about 30.8 % of cases and hydrometallurgical recycling was used in about 69.2 % of cases. The processes that used both hydrometallurgy and pyrometallurgy were divided evenly.

Regarding the end products two different categories have been chosen. These are refined cobalt and cathode materials. The processes that result in refined cobalt are the Sumitomo-Sony process which produces CoO, the Recupyl Valibat process which produces $LiCoO_2$, the Umicore Valéas process which produces $LiCoO_2$, the Glencore and JX Nippon processes which produce refined cobalt and the GEM and Brunp processes which produce cobalt oxides. Lastly, the processes that produce cathode materials are the GEM and Brunp processes. Information on how much of cobalt oxides relative to cathode materials GEM and Brunp produce is difficult to come by, especially in regards to how much cathode materials they produce. It will therefore be assumed that they both entirely produce cobalt oxides. Consequently, all recycled cobalt will be said to be in the form of refined cobalt.

8.6 Geographical Distribution of LIB Recycling

The majority of all LIB recycling occurs in East Asia with as much as two thirds of all global recycling taking place there in 2021 (Baum et al., 2022). This corresponds to about 207 500 tonnes of the total, global, recycling capacity that was about 322 500 tonnes. Furthermore, the majority of this recycling occurs in China, with a capacity of about 188 000 tonnes. The other two big recyclers in East Asia are Japan with a capacity of 21 500 tonnes and South Korea with a capacity of 8000 tonnes. About 92 000 tonnes of LIBs are recycled in Europe, this capacity is spread evenly between France, Belgium, the United Kingdom, Switzerland and Germany. North America has a recycling capacity of about 20 500 tonnes that is split between the United States and Canada. Facilities capable of recycling about 40 000 tonnes of LIBs are however planned. Consequently, 58.3 % of all recycling takes place in China, 28.5 % in Europe and 6.67 % in Japan (Baum et al., 2022).

8.7 Recycling and Collection Rate of Cobalt in LIBs

The actual recycling rate of LIBs varies considerably among different countries. Whilst data specifically for LIB recycling is difficult to come by, data regarding battery recycling as a whole (excluding lead-acid batteries and nickel-cadmium) is available for many EU member states. In 2020 Spain managed to achieve a recycling efficiency, defined here as the ratio of the output fraction of recycled batteries to the output fraction of battery waste (or simply, how much of the material in the battery actually gets recycled), of 91.1 % (the highest reported) whilst Latvia only achieved an efficiency of 52.0 % that same year (Eurostat - European Union, 2023). As was previously mentioned, China recycles the vast majority of all lithium-ion batteries although their overall recycling rate is relatively low. According to an implementation plan brought forward in 2016, China was supposed to reach an LIB recovery rate of at least 40 % by 2020 and, looking further forward, a rate of at least 50 % by 2025 (The State Council of the People's Republic of China, 2017). China was just under this goal in 2019 with a nationwide recovery rate of about 36.3 %. This corresponded to about 129 000 tonnes of LIBs (Sun et al., 2021). Another Asian country with significant LIB recycling capacity is Japan which, like China, has a nationwide recycling rate that can be considered low (Asari and Sakai, 2013).

Due to the great variation that exists among different countries in regard to the recycling rate of LIBs it is difficult to find a representative, singular worldwide value. What exists, however, is the 2006 EU directive regarding recycling of batteries which states that EU member states need to achieve a recycling efficiency of at least 50 % for "other batteries" (batteries that are not lead-acid or nickel-cadmium) (European Union, 2018). It should however be mentioned that this legislation is, today, significantly outdated. LIBs possessed a very small market share back in 2006 making them an afterthought for EU legislators of the time. Additionally, as it was 17 years ago, it is based around recycling technology that today can be considered outdated. New regulations regarding battery recycling efficiency with LIBs in mind were put in place in 2020 but these did not change the current, lowest, recycling rate that is required. They only put forward future targets that have to be reached by a certain point (the earliest of which was by 2025). This means that the current, lowest recycling rate that is required is 50 % (European Union, 2020).

Another important parameter to take into consideration is the collection efficiency of lithium-ion batteries. A high recycling rate will be essentially useless if most batteries never make it to recycling plants. Currently, collection rates are low. In 2017 in Sweden only about 9 % of all lithium-ion batteries that reached the end-of-life stage were collected (206 tonnes vs 2297 tonnes respectively). These numbers can be put into perspective by comparing them to collection rates for alkaline batteries which, in the same year in Sweden, were 68 %. Collection rates in other countries were also low with countries like Germany, the US and Australia reporting rates ranging from 2 to 11 %. LIBs are, however, designed to last for a lot longer than one year which makes it slightly unrepresentative to compare end-of-life numbers from the same year with collection rates. Still, comparing collection numbers with production numbers in Sweden from 6-8 years ago results in a low collection rate, about 16 % (Melin, 2019). Outside of Europe collection rates remained approximately the same. In Japan, for instance, the collection rate was, according to a study from 2013, around 10 %. Another issue with Japan's LIB collection was that, according to the same study, 70% of all batteries do not get removed from the electronic product before the product is disposed of, meaning that most batteries never enter the recycling stage (Asari and Sakai, 2013). Information regarding the collection rate of "other batteries" is, as with recycling rates, available for EU countries. There is again a significant range between different countries with Portugal reaching a collection rate of only 15.6 % in 2020 whilst Iceland reached 76.9 % that same year (which was the highest rate recorded). On average, EU member states reached a collective collection rate of 47.3 % (Eurostat - European Union, 2023).

As the text above shows, it is very difficult to find representative global values for recycling and collection rates. Values tend to vary greatly between countries and information is sparse. Consequently, in order to get an overall, global recycling rate of cobalt from LIB waste, calculations have to be made. To do this an average collection rate (i.e. how many LIBs get collected for recycling after they enter the end-of-life stage) as well as an average cobalt recovery rate (i.e. how much of the cobalt present in the LIB gets recovered in the recycling process) are needed. The collection rate will be based on the total number of LIBs that were recycled in 2023, 322 500 tonnes (Suriyanarayanan et al., 2023). The cobalt recovery rate will be assumed to be 90 % in 2023. Current technology is able to recover more than 97 % of cobalt from an LIB and depending on the technology used the cobalt recovery rate can range from 90 % to as high as 99 %. Hydrometallurgical recycling does tend to reach rates of 90 % and, as this is the dominant recycling method, and in order to be conservative, this will be used as the estimate going forward.

With this information a recycling rate can now be calculated. By taking the value for total cobalt demand in 2021, 175 000 tonnes, and how much of that cobalt is used for LIBs, around 65 %, a value representing how much cobalt was used in LIBs in 2021 can be found, 99 700 tonnes. This value can then be compared to how many tonnes of cobalt is recycled from LIBs every year. The recycling value can be found by multiplying the total amount of LIBs that were recycled in 2021, 322 500 tonnes, with the market share and cobalt content in the five dominating cathodes found in LIBs and then multiplying that by the cobalt recovery rate of 90 %. This resulted in a total amount of recycled cobalt of 27 429 tonnes. LIB lifetime was previously assumed to be, on average, 10 years (based on current technology). The LIBs that enter the end-of-life stage should thus be approximately 10 years old though it is here set at 8 years to account for technological advancements in the last 10 years. Thus, taking values for cobalt demand (for LIB production) from 2013, 44 000 tonnes, and dividing the total amount of recycled cobalt in LIBs (27 400 tonnes) with this value a recycling rate could be calculated. The recycling rate was thus 62.4 %. These calculations were carried out in Google Sheets.

9 Transportation of Cobalt

Cobalt is transported long distances throughout its life cycle. These transports require large vehicles, from trucks to heavy cargo ships, and release large amounts of emissions, toxic waste and other harmful substances. A major source of these emissions is fuel use as many trucks use diesel and virtually all bulk carriers and cargo ships run on fossil fuels (specifically heavy fuel oil) (99% as of 2021) (IRENA, 2022). Both types of transports consequently release large amounts of CO_2 and other greenhouse gasses. They also release large amounts of particulate matter which has the potential to be carcinogenic. The exact transport route was described in Appendix E along with more in depth explanations but is summarized in Table 5 and Table 6. The first table shows the route of primary cobalt and the second the route of secondary cobalt. As cobalt is extracted, processed, refined etc. in many different places there are several different ways cobalt can be transported throughout its life cycle. This report only looked at two variations of two different routes which were based on the locations where the majority of each step takes place. LIB usage was assumed to be divided between the US and China. The distance and consequent CO_2-eq emissions of each individual transport is calculated using NTMCalc 4.0 (NTMCalc 4.0, 2023).

Table 5: Presents data for all transports of primary cobalt. Divided between pre-use transports, transports if use stage takes place in the USA and if use stage takes place in China. Displays distance and percentage of total mass. *T* denominates truck transport and *S* denominates ship transport.

Transport	Distance [km]	Percentage of total mass
Pre-Use		
Kolwezi-Matadi (T)	2325	100
Matadi-Shanghai (S)	19043	100
Shanghai-Quzhou (T)	405	100
Quzhou-Ningde (T)	410	100
Use in USA		
Ningde-New Jersey (S)	20626	50
New York-Albany (T)	245	18.8
New Jersey-Shenzhen (S)	21390	31.2
Shenzhen-Ningde (T)	909	31.2
Use in China		

Ningde-Beijing (T)	1812	50
Beijing-Beijing (T)	0	18.8
Beijing-Tianjin (T)	149	31.2
Tianjin-Ningde (T)	1672	31.2

Table 6: Presents data for all transports of secondary cobalt. Divided between pre-use transports, transports if use stage takes place in the USA and if use stage takes place in China. Displays distance and percentage of total mass. *T* denominates trucks and *S* denominates ships.

Transport	**Distance [km]**	**Percentage of total mass**
Pre-Use		
Shenzhen-Ningde (T)	909	50
Tianjin-Ningde (T)	1672	50
Use in USA		
Ningde-New Jersey (S)	20626	50
New York-Albany (T)	245	18.8
New Jersey-Shenzhen (S)	21390	31.2
Shenzhen-Ningde (T)	909	31.2
Use in China		
Ningde-Beijing (T)	1812	50
Beijing-Beijing (T)	0	18.8
Beijing-Tianjin (T)	149	31.2
Tianjin-Ningde (T)	1672	31.2

10 Technological Advancements

As with all things, technology will inevitably be changed by the unstoppable march of time. The rapidly approaching future will see changes, both small and large, that will affect the realm of cobalt. Exactly which will break through is impossible to predict with certainty but much research has been made and many proposals have been brought forward, some of which will be documented in the following section.

10.1 Improvements in Cobalt Extraction

The first step in the process diagram of cobalt is extraction, and this is also the earliest step where technological improvements can be made. Current cobalt extraction technology has significant adverse effects on the environment. Cobalt mining releases hazardous substances ranging from carcinogenic particles, radioactive emissions and particles capable of causing heart and vision problems. Cobalt on its own can, in addition, cause pneumonia or asthma and can accumulate in nature in fruits, seeds, soils, plants and water. These consequences of cobalt mining clearly show the necessity of improvements. One major reason for these effects is that cobalt extraction uses large amounts of fossil fuels. Fossil fuel usage occurs both in general electricity generation (in the form of coal) as well as blasting (in the form of oil). Due to this, technological improvements in the extraction step does not necessarily need to incorporate any new, complicated technologies. Simply replacing the fossil fuels with greener alternatives will cause the process to have less of a negative impact (Farjana et al., 2019).

10.2 Future Extraction Techniques

The cobalt that is discussed in this report is assumed to come from conventional extraction sources, i.e. open-pit, underground and artisanal mining. Cobalt does, however, exist in large quantities elsewhere (not solely in the ground) and different ways of acquiring and extracting it have been proposed. It is possible that these methods will become relevant in the future and they will thus be discussed here.

10.2.1 Phytomining

Phytomining is a possible future extraction technique that is related to using plants that gather the cobalt directly from the soil. It, specifically, utilizes a hyper-accumulator plant capable of absorbing cobalt in the soil that is, after accumulation is complete, harvested and combusted. This leaves ash with high cobalt content also known as bio-ore. The ash undergoes sintering, smelting and acid dissolution which produces a leachate that, if it undergoes electrowinning, will release the metals. Phytomining has been shown to be feasible to some extent though problems exist for cobalt. The earliest proposals used Ni-accumulating plants that, while possible to use, would only be capable of gathering a limited amount of cobalt. Another possibility is, however, found when looking at the plants growing near the Katanga Copper Belt. One plant, *Haumaniastrum robertii*, has been shown to accumulate cobalt concentrations higher than 4000 micrograms/g in their leaves and could therefore be a possible phytomining candidate (Earl et al., 2022; Lange et al., 2017).

10.2.2 Deep Sea Mining

On 7 March 1873 the HMS Challenger hauled up multiple pieces of metal from the bottom of the West Atlantic Ocean. These metals were reported to be "...round and had a diameter of 0-1 mm" and were identified as manganese (Thomson and Murray, 1911). This modest haul marked the beginning of humanity's attempts at deep sea mining. As was mentioned earlier on, submarine deposits of cobalt are estimated to range between 1.6 million tonnes to 120 million tonnes worldwide, clearly showcasing why countries and companies are so keen on developing deep sea mining technology. Currently, three different types of deep sea deposits are of interest as they contain the majority of deep sea metals. These types are polymetallic nodules on the seabed, sulfide deposits found near hydrothermal vents and ferromanganese crusts found on seamounts and crusts. Out of these, ferromanganese crusts are of particular interest as they contain large amounts of cobalt (up to 2 % cobalt). These crusts occur at depths between 400-5000 m in areas with particularly high volcanic activity and grow from precipitated metals (International Seabed Authority, 2023a; Ma et al., 2017; U.S. Government Accountability Office, 2021). A more technical discussion concerning deep sea mining and how it can be carried out can be found in Appendix F.

As of today, 22 contractors ranging from corporations to governments have entered into contracts with the International Seabed Authority (ISA) with the intention of exploring the deep sea with the eventual intention of establishing deep sea mines (though as it stands no actual deep sea mining has commenced). As it stands, 5 of these 22 contractors are exploring the possibility of mining cobalt in ferromanganese crusts. These five contractors are South Korea, China, Russia, Japan and Brazil. All of these contractors operate in the Pacific Ocean (specifically the western Pacific) except for Brazil which operates in the South Atlantic (International Seabed Authority, 2023a, 2023b).

10.2.3 Asteroid Mining

Since 1991, when the space probe Galileo passed the asteroid Gaspara, asteroids have been under close scrutiny of researchers with the goal of finding out how these celestial bodies can be beneficial to Earth's interests. As some of the key resources vital to technology (e.g. cobalt) are already scarce and might even run out relatively soon, extracting precious metals from asteroids has been proposed by some scientists to alleviate this problem (Feinman, 2013). To accurately describe asteroid mining, it is important to first describe the types of asteroids relevant to mine, carbonaceous asteroids and type M asteroids (Andrews et al., 2015). Carbonaceous, or C-type/C-complex, asteroids are the most common types of asteroids in the solar system and are formed from leftover materials from the formation of planets and most likely mainly consist of clay and silicate rocks (Davis and Carney, 2023; Watanabe et al., 2019). From an asteroid mining perspective, C-type asteroids are not only interesting due to high metal content, but also due to the water that can either be used as/or converted to propellant or brought back to Earth (Andrews et al., 2015).

Type M asteroids (or metallic asteroids) are much less common than C-type asteroids but are as a rule richer in metal content and as such even more interesting from an economic perspective (Bowell et al., 1978; Davis and Carney, 2023). The M-type asteroids are characterized by their reddish spectra and are hypothesized to be cores of lesser planets, which have lost their outer, rocky, layer due to collisions (Lupishko and Belskaya, 1989). The composition of metallic asteroids depends on the distance from the sun the asteroid was formed, where those exposed to high temperatures could have a basalt surface and iron "core" unlike those further from the sun where lower temperatures would avoid this partial melting (Davis and Carney, 2023).

Both the C-type and M-type asteroids can contain large amounts of several different metals, including, but not limited to, iron, nickel, cobalt, gold and platinum. The exact amount of these metals the asteroids contain, and their value, vary wildly between different sources but the common consensus is that there could be enormous reserves of metals in just one asteroid (Andrews et al., 2015; Feinman, 2013; Webster, 2023; Yarlagadda, 2022). One example of this is the asteroid 16 Psyche, which accounts for about 1 % of the total mass of the asteroid belt and has been estimated to have a worth of 10 000 quadrillion dollars (Petrescu, 2020). This amount is however most likely a very significant overestimation and a more realistic estimation is that of 27.7 billion dollars (Kelley, 2021). With this in mind, it can be said that economic incentive for asteroid mining exists. Regarding the cobalt content of an asteroid, it is estimated that a single asteroid with a diameter of around 1 km contains about 1.5 million tonnes of metallic cobalt (Feinman, 2013). This can be compared with the 25 million tonnes of cobalt reserves left on Earth leading to the conclusion that if asteroid mining becomes feasible, cobalt scarcity would not ensue. An in-depth description of how asteroid mining could be performed and possible legal ramifications can be found in Appendix F.

10.3 Improvements in LIB Technology

A more grounded approach to either increasing the cobalt supply, decreasing the cobalt used or otherwise improving the Li-ion manufacturing process in relation to cobalt, is improving the processes, techniques and technology used to manufacture LIBs or the Li-ion batteries themselves.

10.3.1 Improvements in LIB Manufacturing

The LIB manufacturing process, electrode preparation, cell assembly and electrochemistry activation as described earlier, can be improved regarding cost, energy use and/or processing time. The solvent recovery and drying step as well as the formation/aging step are of extra importance as they represent the largest energy consumption fraction (Liu et al., 2021).

Regarding the solvent recovery, one option to decrease both energy use and environmental impact is to replace the toxic organic solvent with a water-based solvent as is used for the anode. This is however not completely unproblematic as the water can partially degrade the cathode and decrease the capacity. Another option is to completely forego the solvent and use alternative technologies like dry painting or electrostatic spraying, which has been more successful than solvent substitution as it has resulted in battery cells of comparable or even better quality than conventional techniques (Ludwig et al., 2016). It is also possible to improve the currently used drying techniques by utilizing a fiber laser to decrease the energy consumption by 50 % (Liu et al., 2021).

The other manufacturing step where improvement is mainly needed, formation/aging, is very energy intensive due to the long time (up to three weeks) spent in a drying room and the charging/discharging vital to a well-functioning formation process. Some research shows that the formation/aging process time could be halved for LCO batteries by stopping the charge/discharge cycles when they reach 3.7 V instead of the customary 4.2 V, while other research found that running the charge/discharge cycles repeatedly at 3.9-4.2 V decreased the formation time for NMC cells to 14 h. These techniques could be viable in the future but are not as mature technologies as the previously mentioned LIB manufacturing improvements which have been more reliably tested as of today (Davoodabadi et al., 2019; Liu et al., 2021).

10.3.2 Improvements in LIB Lifetimes

An obvious way of improving LIBs with the intention of reducing cobalt scarcity is to increase the lifetime of the batteries. Plenty of research has been made with the intention of finding different ways of achieving this. These tend to range from technological improvements of the battery and the device or vehicle using it, to proposals connected to changing the way the batteries are used. One report from 2021 found that the lifetime of batteries used in electric buses could be increased by 20 % via integration of a flywheel. A flywheel acts as a type of secondary energy storage system (the whole system is known as a Flywheel Energy Storage System or FESS) and helps improve the power and energy efficiency of the battery and, consequently, increases battery lifetime (Glücker et al., 2021). Another report from 2018 investigated the effect of the state of charge (SOC), literally defined as the amount of electrical charge in the battery (Tribioli and Bella, 2022), on battery aging. The report found that restricting SOC to only 50 % had significant effects on lifetime, with increases ranging from 44-130 % (Wikner and Thiringer, 2018).

A different approach to improving LIB lifetime is to make the charging of the batteries more efficient. The optimal way to charge an LIB has been investigated in several studies. The so-called “optimized charging profile” is based on several parameters ranging from charging time, depth of discharge and charging current and can, if found out for different types of batteries, greatly contribute to increasing overall battery lifetime. By doing this, one report managed to extend the lifetime of an LIB by 27 % (Maia et al., 2019). Changing the charging profile will, to some extent, require the user of the battery to behave differently which makes improvements in this area more difficult (specifically less certain) than simply changing the battery but, if better use and charging of batteries is encouraged, can happen.

A similar area of improvement to changing the charging profile is to change the way the batteries are used throughout their lifetime. One method that has been found to increase lifetime in this area is derating. Derating is defined as not operating an electronic or electric device at its maximum capacity. A 2021 report on this area found that LIB lifetime could be increased by as much as 65 % by utilizing what they call, "degradation-aware derating". They, by accounting for and predicting the degradation of the battery, found the maximum current the battery should be run at in order to maximize lifetime. Additionally, the derating actually allowed the battery to outperform the manufacturer's specifications, showing the great potential of this process (Schimpe et al., 2021). Improvements in this area, like optimizing charging, will require action by the consumer but battery lifetime should be able to be improved by spreading information and encouraging better use of the battery. Additionally, battery manufacturers could provide their own derating guides for their batteries.

10.3.3 Substitution of Cobalt

A possible way to decrease cobalt demand is by substituting cobalt in battery cells, either by replacing the cobalt with other materials directly, i.e. decreasing the cobalt content of e.g. NMC cathodes (Yang et al., 2019), or by exchanging cobalt-based cathodes with cathodes containing less or no cobalt. The concept of substituting cobalt for other materials due to price changes and/or availability is not a novelty. As was mentioned earlier, following the second Shaba Crisis in 1978, the price of cobalt skyrocketed resulting in a major shift in cobalt use and demand. An effect of this was the investment in research and development to find an alternative to the then dominating magnetic alloy, samarium-cobalt (SmCo), resulting in the creation of the neodymium iron boron (NdFeB) alloy. The NdFeB alloy allowed for the production of even stronger permanent magnets than SmCo leading to the substitution of the cobalt-containing magnetic alloy for most applications (Speirs et al., 2013).

As seen in this historical example, it is not unreasonable to assume that possible future increases in cobalt demand and decreases in cobalt supply would result in the substitution of cobalt in Li-ion batteries. This would then naturally affect the market shares of the main five lithium ion cathodes and thus the environmental effects of LIBs as a whole. As mentioned earlier, the current market share of the main LIB cathodes are as follows: LCO, 21 %, LFP, 36 %, LMO, 8 %, NCA, 9 %, and NMC, 26 % (Zeng et al., 2022b).

In a future scenario, LCO cathodes will be of lesser importance (Porzio and Scown, 2021), mainly due to their high cobalt content and relatively short lifetime making them unsuitable for

EVs (Månberger and Stenqvist, 2018). They are projected to have a market share of less than 15 % in 2030 due to the stagnation of the consumer electronics sector and rapid growth of the EV market (Zubi et al., 2018).

Conversely, the future of LFP cathodes is relatively bright, despite issues with low capacity, due to the high safety and long battery life they offer. Because of these characteristics, the LFP cathodes are less suitable for electric cars but well suited for heavy-duty vehicles like buses, which has been realized in large scale by the Chinese company BYD (Ding et al., 2019). As such the market share of LFP cathodes is projected to increase in the future (Zubi et al., 2018).

LMO cathodes are as mentioned above only suitable for niche applications due to their limitations (Gourley et al., 2020). As such, the use of them is assumed to be limited in the future even though they are cobalt-free. As for 2030, the projected market share of LMO cathodes is about 10 %.

Regarding the NCA cathode, cobalt substitution is a very viable alternative for the future. As shown in a report from 2019, (Li et al., 2019), all cobalt in NCA batteries can be substituted with Mn and Al without any noticeable changes in battery functionality. It is thus assumed that the NCA cathodes will be completely cobalt-free in the near future. The future market share of NCA combined with LFP is projected to be 40 % as of 2030 (Zubi et al., 2018).

As NMC cathodes have differing metal compositions (more or less Ni/Mn/Co) the natural step to reduce cobalt content is to shift from the more cobalt-intensive NMC cathodes like NMC111 (20.4 weight-% Co) to NMC622 (12.2 weight-% Co) and/or NMC811 (6.1 weight-% Co). This is a currently ongoing process that, except the obvious decreased cobalt usage, would affect the (NMC) battery capacity positively but the cycle and thermal stability negatively. There are however some prospective manufacturing techniques like micron scale single-crystal or core-shell synthesis that could alleviate these issues (Gourley et al., 2020). For this study it is assumed that all NMC111 batteries are substituted with equal shares of NMC622 and NMC811 in the near future. The market share of NMC cathodes for 2030 is projected to be 35 % and thus represent the largest share (Zubi et al., 2018).

10.4 Improvements in Transport of Cobalt

10.4.1 Improvements in Truck Transports

Several improvements regarding transportation are possible and likely to come into use before 2050. An IEA report from 2018 outlined and discussed several ways of improving and reducing the fuel usage, energy usage and emission rate of trucks by 2050. The scenario looked at three different ways improvements could be made. The first was to implement policies that regulate fuel efficiency via standards and taxes, specifically to introduce a regulatory policy that makes sure all new trucks meet a minimum fuel efficiency standard and to push consumption and purchase of better performing trucks by favoring these models with taxes. The second was to, through increased and improved data sharing and collection, improve transportation logistics as a whole. The final improvement was to implement fuel change and to push trucks using alternative fuels. This would further require researching and improving current fuels and to improve infrastructure in order to make sure these fuels are viable for longer transports. An example of this is to make sure sufficient charging stations exist to support EVs. According to the IEA, implementation of these three improvements could reduce overall fuel demand of trucks by as much as 50 % and emissions by 75 % by 2050 (Teter and International Energy Agency, 2018).

10.4.2 Improvements in Shipping

Improvements will also be made in the shipping industry by 2050. The International Renewable Energy Agency (IRENA) has analyzed how shipping fuel and energy usage as well as emissions will be affected by four different scenarios. The most ambitious of which is the 1.5 °C scenario. IRENA assumes, for this to happen, that the shipping industry will undergo large scale decarbonization by 2050. This will specifically include the implementation of electrical energy and utilization of renewable fuels in the sector. Fossil fuels currently dominate the shipping industry (providing up to 99 % of energy demand as was mentioned previously) but will, in this scenario, be outcompeted by H_2-fuels by 2050. Furthermore, technological and design improvements in ships will reduce the energy demand of ships and make trips cheaper and more efficient. By incorporating all of these improvements IRENA concluded that the overall average energy intensity in the shipping industry could be decreased by 44 % by 2050 (based on 2018 values), from about 0.16 MJ/tonne-mile to 0.09 MJ/tonne-mile. This decrease will be said to be translatable to the decrease in fuel usage in the same period (IRENA, 2022).

11 Description of Scenarios

In the following section the three scenarios developed for this study will be described along with assumptions.

11.1 Scenario I: Business as Usual

The first scenario that was developed in this report was based on current extraction, refining, manufacturing and recycling. This scenario was deemed *Business as Usual* and thus assumed that no improvements were made in the realms of technology related to cobalt extraction and product manufacturing or recycling. The current rate of cobalt use exactly followed future demand, but, as no new deposits were discovered/exploited, the current reserves of cobalt was all that was available. The working hypothesis was that this scenario would lead to cobalt scarcity or, in an extreme case, complete depletion. This scenario, whilst unrealistic, was included in the study for the purpose of comparing it with the other two scenarios that, as opposed to Scenario I, assumed developments that lead to increased cobalt supply and/or decreased cobalt demand. The demand for cobalt in Scenario I was based on extrapolated values from current production (U.S. Geological Survey, 2023) and recycling data (Baum et al., 2022) as well as predictions of high future cobalt demand. Predictions of demand were based on data from Watari et al., 2020 which estimated that it would grow to about 1008 kilotonnes by 2050.

The market share of LIBs has changed drastically from 2013 to 2021, from 43 % to 65 % (Cobalt Institute and Roskill Consulting Group, 2020). It was consequently predicted that usage of LIBs would keep increasing in the upcoming years. Predictions for the compound annual growth rate of the LIB market range from 16.3 % to 11.4 % to over 30 % (Fleischmann et al., 2023; P&S Intelligence, 2022; Research and Markets, ltd, 2023). In all scenarios the market share of LIBs was assumed to grow to 75 % by 2030 (from 65 % in 2021) and further, to 80 % by 2050 in order to stay in line with these predictions.

Based on this, the current total recycled LIBs was used in conjunction with the total cobalt demand for 2021 and the average LIB cobalt content to calculate a rate of recycled cobalt (30.6 %) for 2021, which was then used to calculate primary and secondary supply for 2021, 2030 and 2050. This recycling rate will be static for the *Business as Usual*-scenario regardless of year. *Business as Usual* carbon intensity of relevant countries can be seen in Table 7 and assumptions relevant to this scenario can be seen in Table 8.

Table 7: Carbon intensity for the electricity mix of relevant countries for the *Business as Usual*-scenario.

Country[m]	**Carbon intensity [kg CO_2/kWh]**	**Sulfur intensity [kg SO_2/kWh]**	**Nitrogen intensity [kg NO_x/kWh]**
Australia[a]	0.560	5.76E-04	4.09E-04
Belgium[b]	0.165	1.98E-05	7.15E-05
Canada[c]	0.128	6.25E-05	7.00E-05
China[d]	0.580	6.91E-04	4.40E-04
Democratic Republic of the Congo[e,f]	0.025	0	0
European Union[d]	0.216	1.53E-04	1.45E-04
Finland[g]	0.132	8.09E-05	6.49E-05
Indonesia[h]	0.645	6.75E-04	4.65E-04
Japan[d,i]	0.479	3.37E-04	3.02E-04
Russia[j]	0.345	1.77E-04	2.23E-04
South Korea[d,k]	0.472	3.75E-04	3.16E-04
United States[d,l]	0.353	1.10E-04	3.57E-04

[a] (IEA, 2023a)
[b] (IEA, 2023b)
[c] (IEA, 2023c)
[d] (IEA, 2022c)
[e] (Our World In Data, 2022)
[f] (IEA, 2022d)
[g] (IEA, 2023d)
[h] (IEA, 2023e)
[i] (IEA, 2023f)
[j] (IEA, 2023g)
[k] (IEA, 2023h)
[l] (IEA, 2023i)
[m] Sources used for all countries: (Directorate-General for Climate Action et al., 2021; Réseau de Transport d'Électricité (RTE), 2023; Schlömer et al., 2014; U.S. Energy Information Administration, 2018)

Table 8: Assumptions and outlines made for Scenario I.

Process step	Assumptions
Extraction	All extraction is assumed to have corresponding direct environmental effects as extraction in the DRC (i.e. values are only adjusted for electricity mixes of different countries). 7 % of extracted cobalt is lost to the environment in the mining step.
Processing	Geographical distribution used is from 2019.
Refining	Refining will occur in the same place as processing and their geographical distribution is said to be the exact same.
Product manufacturing	A lithium ion battery pack contains 96 battery cells and weighs approximately 460 kg (Measuring Stuff, 2023; Samsung, 2016).
Transport	Only four transport routes were investigated.
End-of-life	Data from 2019 was used to determine fractions of pyrometallurgical vs hydrometallurgical recycling. 1 kg of LIB cells contain the same amount of cobalt as 1 kg of LIBs.
General Assumptions	75 % of the cobalt market consists of LIBs by 2030, 80 % by 2050. Only the three most relevant countries were investigated for each process step.

11.2 Scenario II: Recycling Rate Improvements

As was seen in the late 1970s when, as a consequence of increased cobalt prices caused by the second Shaba Crisis and the United States increased the amount of cobalt products that were recycled, recycling is a potential way of either evading cobalt scarcity or reacting to it. This report therefore aimed to investigate the effects on cobalt if the recycling of cobalt products was both increased and maintained. The second scenario was based on this and was referred to as *Recycling Rate Improvements*.

According to a proposal made by the European Commission in December 2020, concerning the regulation of batteries and waste batteries, some goals with varying ambitions have been set regarding LIB recycling in the EU. The high ambition goal stated that, by 2030, LIB recycling efficiency (or recycling rate) should reach 70 % and that cobalt recovery rates should be as high as 95 %. The medium ambition was, on the other hand, to reach a recycling rate of 65 % in 2025 and a cobalt recovery rate of 90 % (European Commission, 2020; European Parliament, 2022). A 95 % cobalt recovery rate is very high but, simultaneously, a realistic goal. One study published in 2023 found, for instance, that cobalt recovery rates higher than 97 % were achievable (Suriyanarayanan et al., 2023). The Swedish government has a standing goal of collecting at least 95 % of all car and industrial batteries (thus including LIBs) (Klimat- och näringslivsdepartementet, 2008).

The second scenario was based around the high ambition goal proposed by the European Commission and the LIB collection rate set by the Swedish government. It aimed to project what peak LIB recycling could look like. The cobalt recovery rate as well as the LIB collection rate was thus said to reach 95 % by 2030 and these levels were said not to change over the upcoming years. The rates increased linearly from the starting rate of 62.4 % up until 2030 and were assumed to apply globally. This resulted in an overall recycling rate of 90.25 % which consequently was higher than the European Commission's goal of 70 % (see Figure 11). Parameters and assumptions of this scenario are summarized in Table 9 and Table 10.

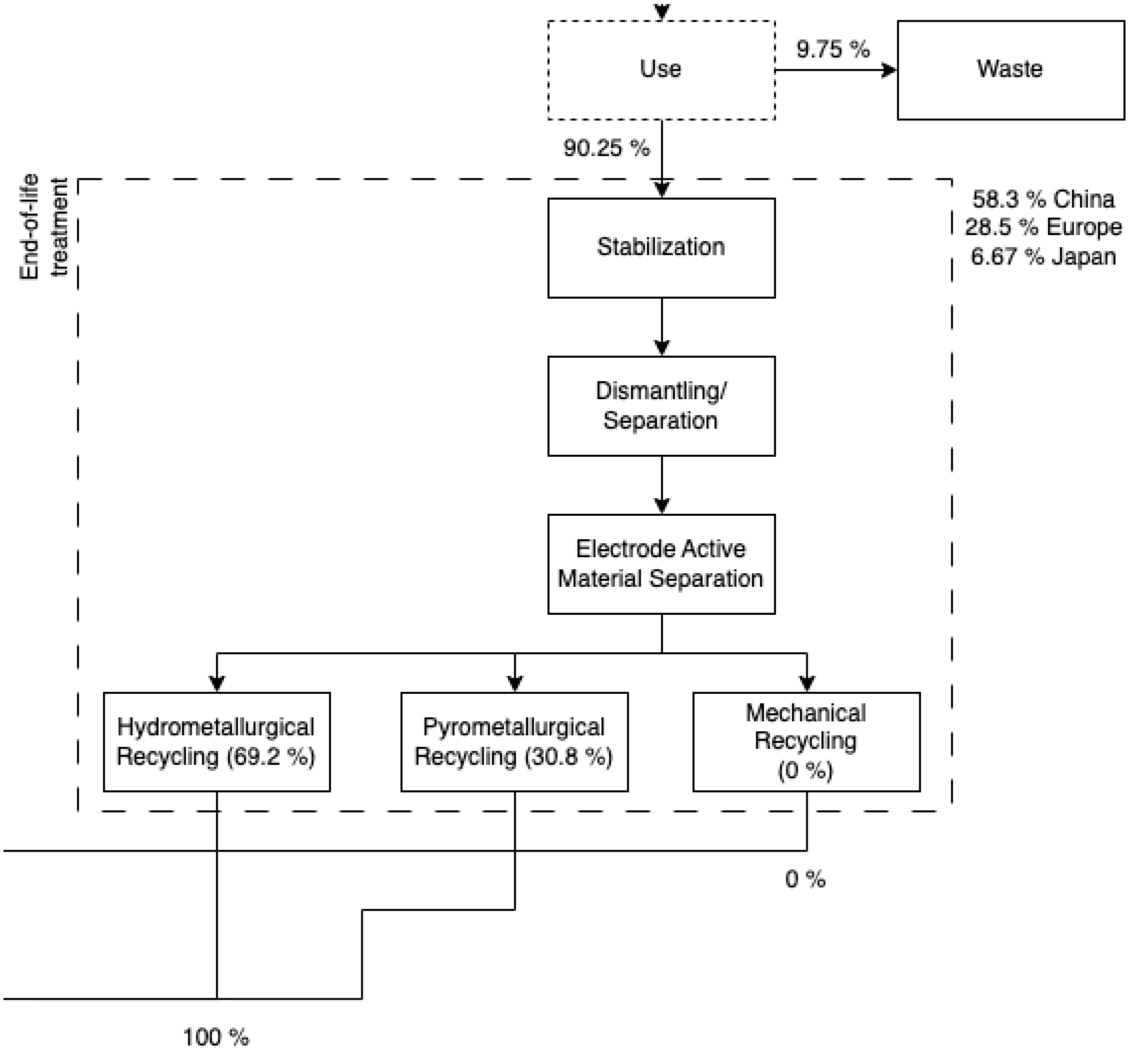


Figure 11: Flow chart representing the end-of-life stage for Scenario II. Presents a new recycling rate value.

Table 9: Parameters distinguishing Scenario II from Scenario I.

Parameter	Description
1	Recycling rate increased from 62.4 % to 90.25 % by 2030

Table 10: Assumptions and outlines made for Scenario II.

Process step	Assumption
Extraction	All extraction is assumed to have corresponding direct environmental effects as extraction in the DRC (i.e. values are only adjusted for electricity mixes of different countries). 7 % of extracted cobalt is lost to the environment in the mining step.
Processing	Geographical distribution used is from 2019.
Refining	Refining will occur in the same place as processing and their geographical distribution is said to be the exact same.
Product manufacturing	A lithium ion battery pack contains 96 battery cells and weighs approximately 460 kg (Measuring Stuff, 2023; Samsung, 2016).
Transport	Only four transport routes were investigated.
End-of-life	Data from 2019 was used to determine fractions of pyrometallurgical vs hydrometallurgical recycling. 1 kg of LIB cells contain the same amount of cobalt as 1 kg of LIBs. Same energy usage in pyrometallurgical and hydrometallurgical recycling as Scenario I, no change with time.
General Assumptions	75 % of the cobalt market consists of LIBs by 2030, 80 % by 2050. Only the three most relevant countries were investigated for each process step.

11.3 Scenario III: Technological Improvements

The third and final scenario, *Technological improvements*, was based on the assumptions that major technological advancements regarding the mining of cobalt as well as the manufacturing of lithium ion batteries would be achieved. In addition to this the lifetimes of currently existing LIBs were assumed to increase and the cobalt content in Li-ion batteries would, either to anticipate or as a result of a “new Shaba crisis”, decrease in favor of other transition metals. To clearly differentiate this scenario from Scenario I and II, the technological advancements were assumed to be fully implemented by 2030.

The improvement in cobalt extraction was assumed to cover the type of energy used, as it would entail a shift from fossil energy to green energy, as well as improvements in fuel efficiency. For LIB manufacturing, it was assumed that drying and solvent recovery were replaced by dry painting or electrostatic spraying, leading to the complete removal of the energy demand for solvent recovery of about 420 kWh per LIB and a reduction of 20 % in energy use respectively (this is a conservative estimate due to the lack of numerical data but presence of clear indications that the energy used is lower) as well as that no toxic solvent is used. It was also deemed that the drying time and, as such, the drying energy use is halved using lower maximum voltage during the charging/discharging cycles (Liu et al., 2021).

The lifetime of LIBs were assumed to double (from 10 to 20 years) using a combination of the technologies and techniques such as flywheels and derating mentioned earlier (Zeng et al., 2022a). The substitution of cobalt was slightly more complicated as it depended on two factors, the substitution of cobalt-containing batteries with cobalt-free ones, and the substitution of cathode-locked cobalt with other transition metals. The first type of substitution was a mere change in LIB cathode market shares and the different cathodes went from and to the following market shares: LCO 21 % ⇒ <15 %, LFP 36 % ⇒ 33 %, NCA, 9 % ⇒ 7 % (LFP + NCA, 45 % ⇒ 40 %), LMO 8 % ⇒ 10 %, NMC 26 % ⇒ 35 % (Zeng et al., 2022a; Zubi et al., 2018). The second form of substitution represented a change in weight percent (wt-%) of cobalt for the different types of cathodes and were changed as follows: LCO 18.5 % ⇒ 18.5 %, LFP 0 % ⇒ 0 %, LMO 0 % ⇒ 0 %, NMC 20.4 % ⇒ 9.2 %, NCA 2.9 % ⇒ 0 % (Melin, 2019; Zubi et al., 2018). Parameters and assumptions for the scenario can be seen in Tables 11 and 13 whilst projected carbon intensity of relevant countries in the future is seen in Table 12.

Table 11: Parameters distinguishing Scenario III from Scenario I.

Parameter	Description
1	Fuel use for extraction is reduced by 50 % compared to Scenario I.
2	64.8 % reduction in total energy use in the LIB manufacturing step
3	LIB lifetime increased from 10 years to 20 years
4	Cathode market share changes: LCO 21 % ⇒ <15 %, LFP 36 % ⇒ 33 %, NCA, 9 % ⇒ 7 % (LFP + NCA, 45 % ⇒ 40 %), LMO 8 % ⇒ 10 %, NMC 26 % ⇒ 35 %

5	Cobalt content (weight percentage) changes: LCO 18.5 % % ⇒ 18.5 %, LFP 0 % ⇒ 0 %, LMO 0 % ⇒ 0 %, NMC 20.4 % ⇒ 9.2 %, NCA 2.9 % ⇒ 0 %
6	Electricity mix change: See Table 11

Table 12: CO_2-, SO_2- and NO_x-intensity for the electricity mix of relevant countries for the *Technological Advancements*-scenario. All values are projected for 2050 with the exception of the value for the DRC which is projected for 2040 due to lack of data.

Country[m]	**Carbon intensity [kg CO_2/kWh]**	**Sulfur intensity [kg SO_2/kWh]**	**Nitrogen intensity [kg NO_x/kWh]**
Australia[a]	0.124	3.90E-05	6.55E-05
Belgium[b]	0.056	0	0
Canada[c]	0.0528	1.06E-07	1.16E-05
China[d]	0.111	7.58E-05	5.55E-05
Democratic Republic of the Congo[e]	0.0598	0	0
European Union[f]	0.088	3.14E-07	3.42E-05
Finland[g]	0.049	0	0
Indonesia[h]	0.358	3.58E-04	2.38E-04
Japan[i]	0.076	1.09E-04	9.43E-05
Russia[j]	0.274	1.62E-04	1.74E-04
South Korea[k]	0	0	0
United States[l]	0.255	1.10E-04	1.57E-04

[a] (Aurora Energy Research, 2023)

[b] (FPS Public Health - DG Environment, 2021)

[c] (Government of Canada, 2022)

[d] (Energy Research Institute, 2015)

[e] (IEA, 2022d)

[f] (Directorate-General for Climate Action et al., 2021)

[g] (AFRY, 2020)

[h] (Secretary General of the National Energy Council et al., 2019)

[i] (Cabinet Secretariat et al., 2021)
[j] (Garanina and Mima, 2020)
[k] Governmental goal, not prediction (Green Energy Strategy Institute et al., 2022).
[l] (U.S. Energy Information Administration, 2022)
[m] Sources used for all countries: (Kolodziejczyk, 2023; Réseau de Transport d'Électricité (RTE), 2023; U.S. Energy Information Administration, 2018)

Table 13: Assumptions made for Scenario III.

Process step	Assumptions
Extraction	All extraction is assumed to have corresponding direct environmental effects as extraction in the DRC (i.e. values are only adjusted for electricity mixes of different countries). 7 % of extracted cobalt is lost to the environment in the mining step.
Processing	Geographical distribution used is from 2019.
Refining	Refining will occur in the same place as processing and their geographical distribution is said to be the exact same
Product manufacturing	Electrostatic spraying uses 80 % of the energy used by slurry casting. A lithium ion battery pack contains 96 battery cells and weighs approximately 460 kg (Measuring Stuff, 2023; Samsung, 2016).
Transport	Only four transport routes were investigated.
End-of-life	Data from 2019 was used to determine fractions of pyrometallurgical vs hydrometallurgical recycling 1 kg of LIB cells contain the same amount of cobalt as 1 kg of LIBs Same energy usage in pyrometallurgical and hydrometallurgical recycling as Scenario I, no change with time
General Assumptions	No technological advancements (i.e. no new processes/machines) for processing, refining and end-of-life. Only the three most relevant countries were investigated for each process step.

12 Results: Scarcity

Results related to scarcity are presented in this section. This includes primary and secondary supply fractions as well as how much cobalt is used in each scenario. As a reminder current estimates put total terrestrial reserves of cobalt at 8.3 million tonnes and current resources at 25 million tonnes.

12.1 Scenario I: Business as Usual

The first scenario, being based on current technology, usage and recycling, results in Figure 12. Cobalt demand for LIBs grows to 1008 kilotonnes (based on Watari et al., 2020) by 2050 and, as the overall recycling rate remains the same (62.4 %), primary supply (i.e. new mined cobalt) has to grow significantly (by 584 %) to keep up with this demand. Primary supply in 2021 is calculated to be 92.8 kilotonnes which will grow to 279 kilotonnes by 2030 and further to 635 kilotonnes by 2050. This corresponds to a total primary cobalt usage between 2021 and 2050 of 10 810 kilotonnes. Secondary supply will go from 27.4 kilotonnes of cobalt in 2021, to 70.9 kilotonnes in 2030, and finally to 417 kilotonnes in 2050. Adding together the primary and secondary supply results in a value higher than the demand (1052 kt vs 1008 kt). This is due to the fact that 7 % of primary cobalt is lost during extraction and, consequently, that extra cobalt has to be mined.

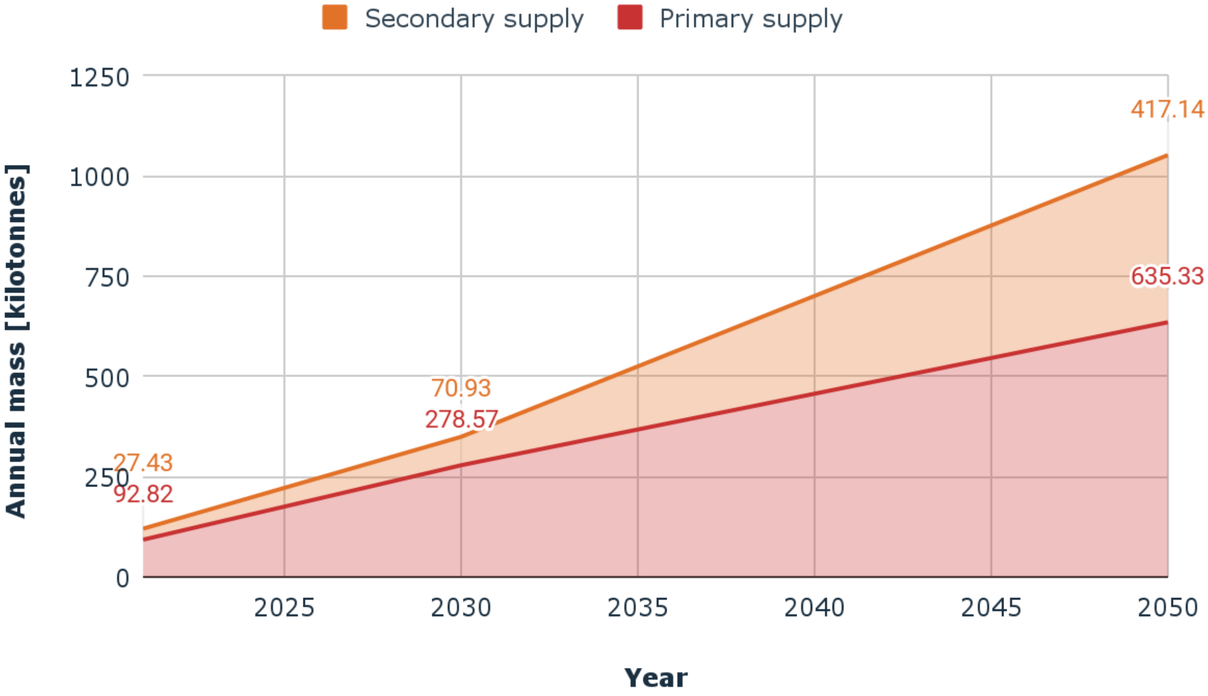


Figure 12: Yearly demand for virgin cobalt (primary supply) and recycled cobalt (secondary supply) for the *Business as Usual*-scenario as well as total yearly demand.

12.2 Scenario II: Recycling Rate Improvements

As this scenario solely assumes that recycling is improved and, consequently, that LIB technology remains the same as today, the total demand for cobalt in lithium-ion batteries will increase in the same manner as the *Business as Usual* scenario. What will change, however, is the total demand for new, mined, cobalt. This is logically the case as a much higher percentage of cobalt will come from recycled LIBs.

The results of this scenario are presented in Figure 13. Demand will, as in Scenario I, reach 1008 kilotonnes of cobalt by 2050, but primary and secondary supply will look radically different. Primary supply will be much lower in this scenario, starting from the same amount in 2021, 92.8 kilotonnes, to initially increase to 244 kilotonnes by 2030 to then further increase, albeit at a slower pace, to 434 kilotonnes by 2050. Overall primary cobalt usage is thus also significantly smaller, reaching 8308 kilotonnes of cobalt. Secondary supply will be higher, 103 kilotonnes by 2030 and 603 kilotonnes by 2050.

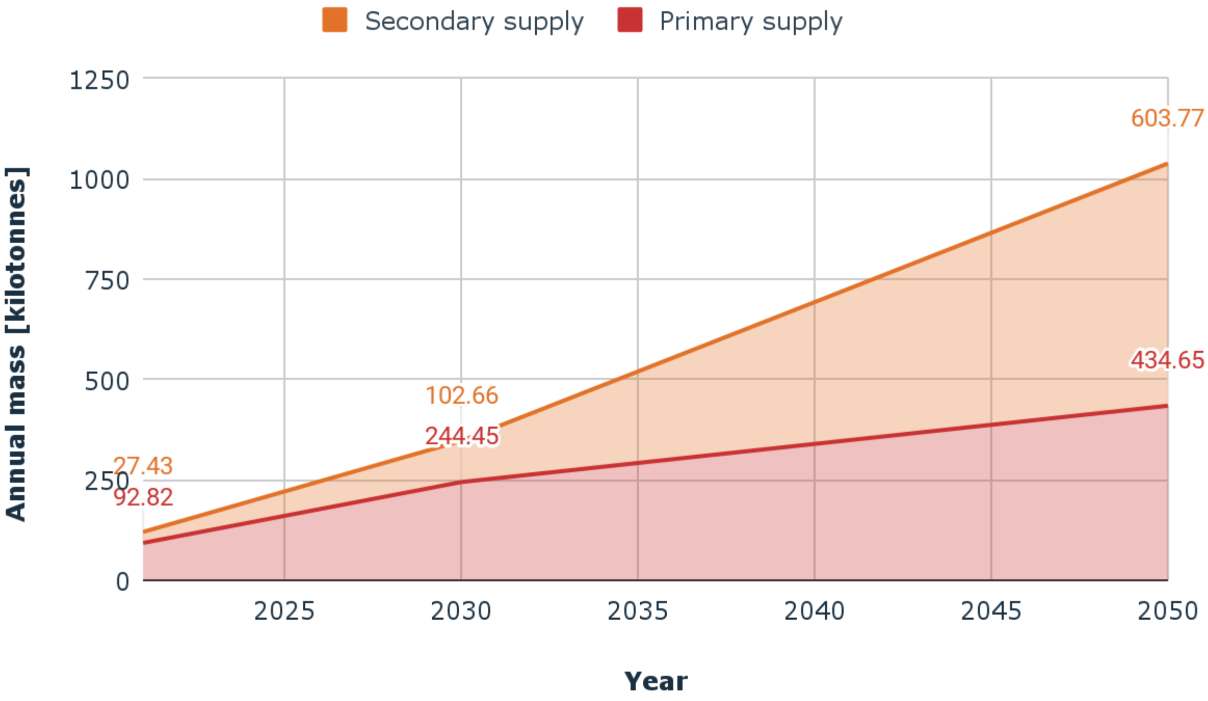


Figure 13: Yearly demand for virgin cobalt (primary supply) and recycled cobalt (secondary supply) for the *Recycling rate improvements*-scenario as well as total yearly demand.

What is necessary for this scenario to be feasible is for cobalt supplies pre-2021 to be large enough to account for (together with primary production) the increase in demand. Secondary supply does not add any new cobalt to the product flow as it is only capable of making cobalt that has already been mined available for secondary (and eventually tertiary, etc.) use. As LIB lifetime is assumed to be 10 years, primary cobalt produced in 2021 for the purposes of LIB production can be said to enter the end-of-life stage in 2030. Assuming all LIBs enter end-of-life at the same time, 114 kilotonnes of cobalt would be available for recycling. Utilizing the 90.25 % recycling rate would mean that 103 kilotonnes of cobalt would be recycled this year. This is significantly less than total demand which means lots of cobalt still has to come from primary sources (244 kt of primary cobalt in 2030).

12.3 Scenario III: Technological Advancements

The third and final scenario differs from the two other scenarios in that it has a lower total cobalt demand (primary + secondary supply), 320 kilotonnes in 2050, due to the substitution of cobalt-intensive LIBs with cobalt-light batteries and doubled LIB lifetime. This can be seen in Figure 14. The primary supply goes from 92.8 to 36.3 to 194 kilotonnes from 2021 to 2030 to 2050 whilst the corresponding values for secondary supply are 27.4, 70.9 and 274 kilotonnes. The overall primary cobalt usage for this scenario is then 3680 kilotonnes. Worth noting is that the recycling rate in this scenario is the same as in *Business as Usual* (62.4 %)

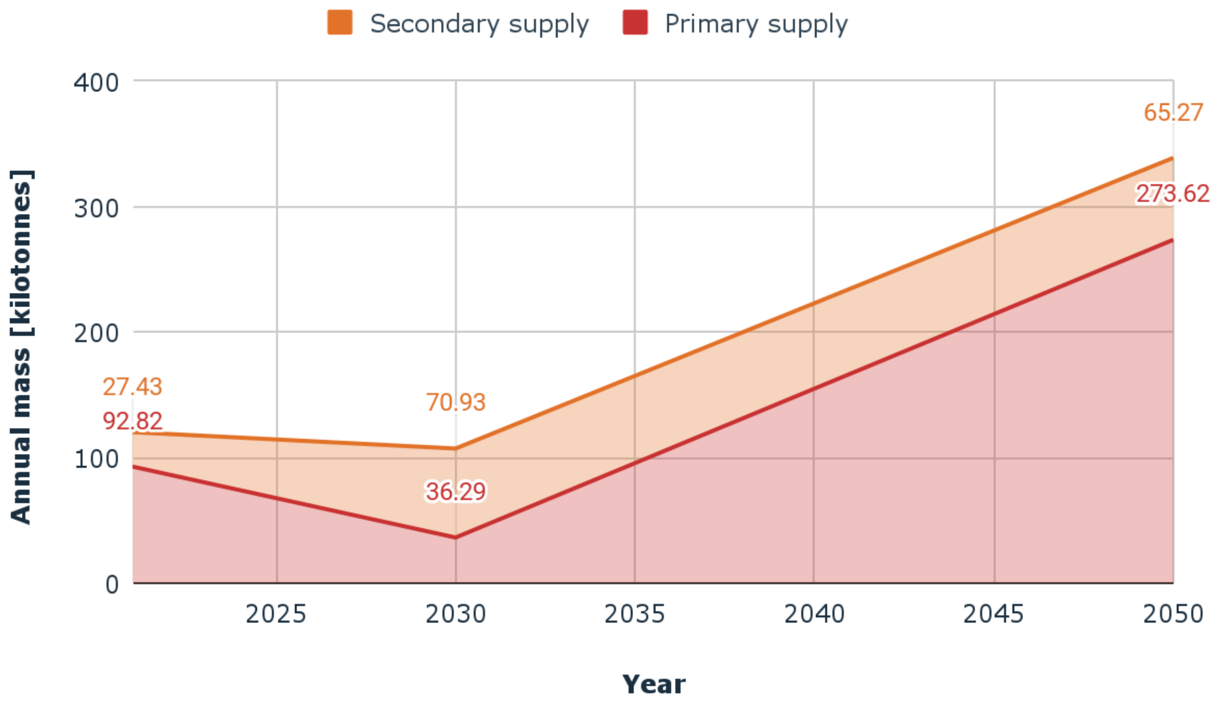


Figure 14: Yearly demand for virgin cobalt (primary supply) and recycled cobalt (secondary supply) for the *Technological advancements*-scenario as well as total yearly demand.

12.4 Primary Supply of All Scenarios

The primary supply for all three scenarios are compiled in Figure 15 below, where it is clear that *Business as Usual* would use the most primary supply of cobalt, followed by *Recycling Rate Improvements* and lastly *Technological Advancements*.

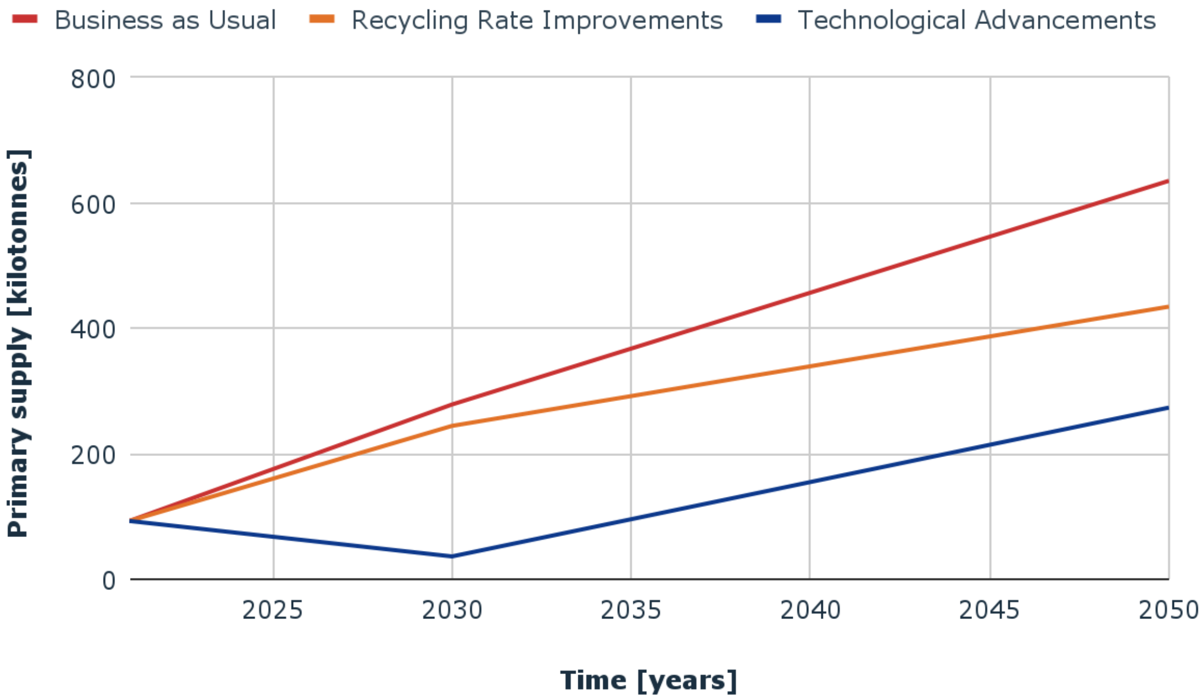


Figure 15: Primary supply (i.e. virgin cobalt required) for each of the three scenarios from 2021 to 2050.

13 Results: Environmental Impact Analysis

Following the scarcity analysis the results will be further analyzed via an environmental impact analysis. This will combine third party data with calculations to get accurate estimates of the environmental impact of each scenario. Furthermore, the results made in the scarcity analysis regarding the amount of primary and secondary cobalt will be taken into consideration in order to accurately allocate the environmental impact of each scenario.

13.1 Description of Results

In depth description of the result as well as calculations and values can be found in Appendix G. The actual results are presented in the following section in the form of graphs.

13.2 Results

Scenarios I, II and III follow the assumptions and outlines mentioned in earlier sections and concretized in Tables 7, 8, 9, 10, 11, 12 & 13 respectively to calculate and produce the figures seen below. These figures visualize the environmental impact of 1 kg of cobalt for Li-ion battery production in 2050 according to the conditions of each scenario.

13.2.1 Global Warming Potential

The global warming potential became 18.0 kg CO_2-eq/FU in the first scenario, 15.9 kg CO_2-eq/FU in the second and 7.51 CO_2-eq/FU in the third (see Figure 16). In the first two scenarios, the product manufacturing stands for the majority of the GWP, while refining and processing are the largest contributing steps for Scenario III (Figure 17).

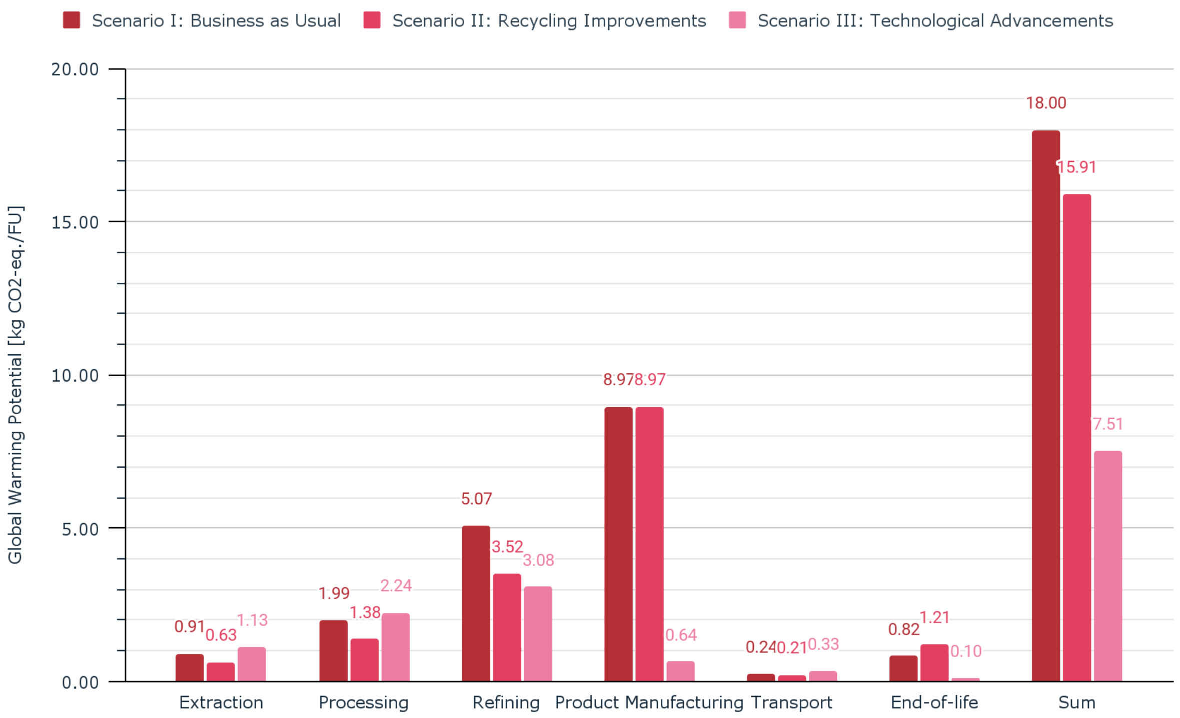
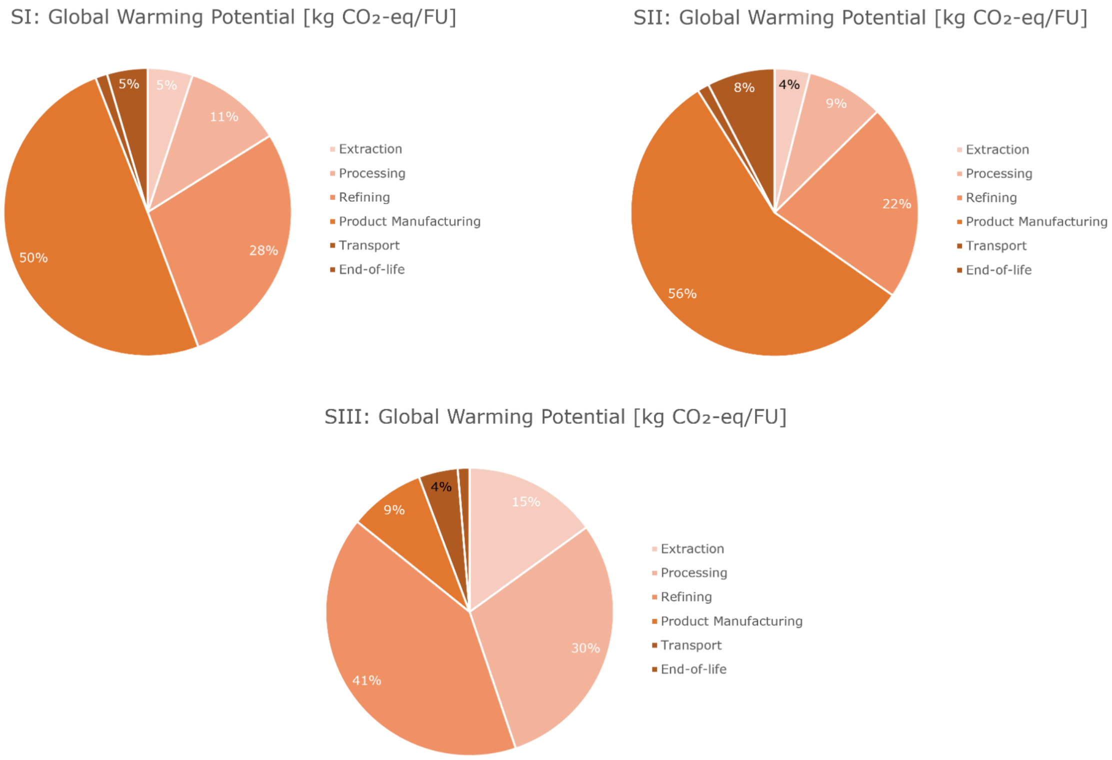


Figure 16: Global warming potential for each process step and scenario presented as kg CO_2-eq/FU.


SI: Global Warming Potential [kg CO₂-eq/FU]

SII: Global Warming Potential [kg CO₂-eq/FU]

SIII: Global Warming Potential [kg CO₂-eq/FU]

Figure 17: Pie chart with global warming potential divided into the process steps of the study.

13.2.2 Aquatic Ecotoxicity Potential

The aquatic ecotoxicity potential can be seen in Figures 18 and 19 below. The total EtP was 16 063 CTU$_e$/FU for Scenario I, 11 138 CTU$_e$/FU for Scenario II and 21 485 CTU$_e$/FU for Scenario III. As visualized in Figure 19 below, almost all of the contribution to the aquatic toxicity comes from the extraction and processing & refining steps.

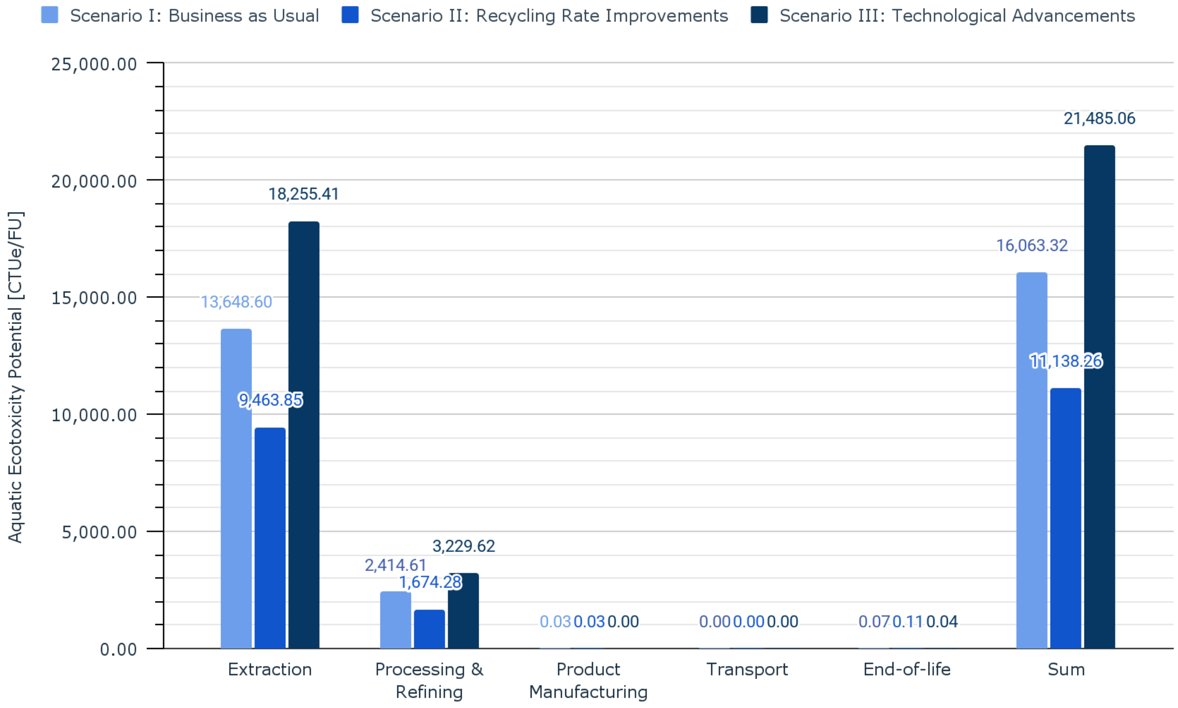


Figure 18: Aquatic ecotoxicity potential for each process step and scenario presented as CTU$_e$/FU.

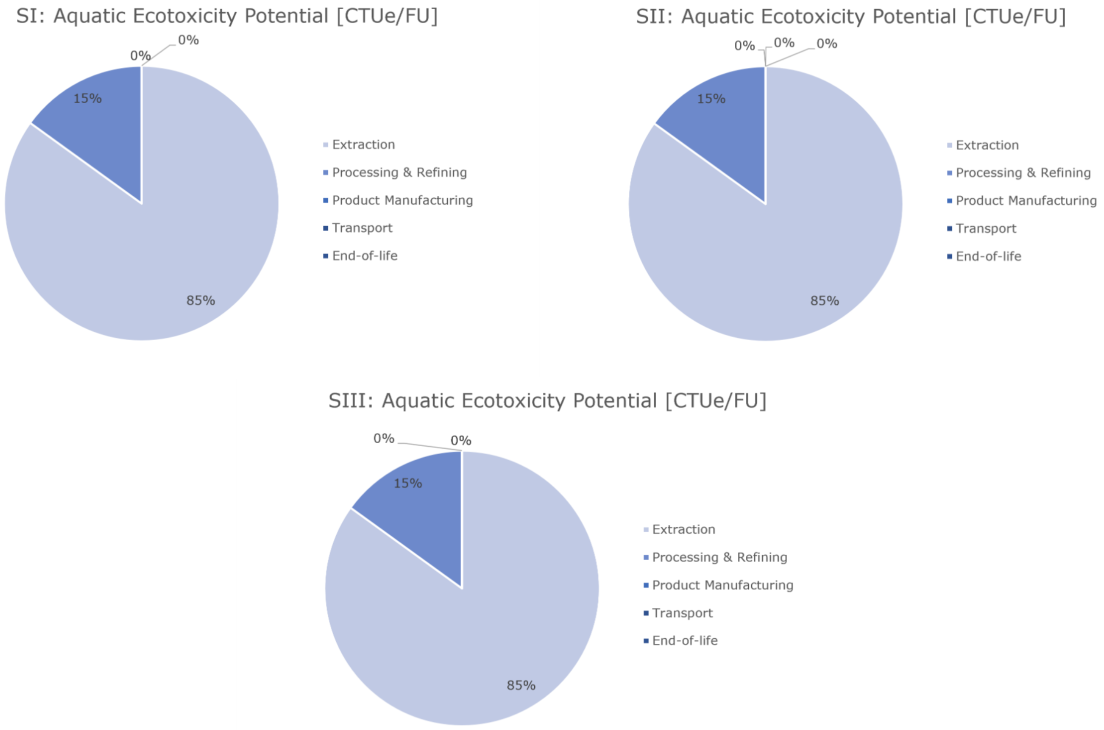


Figure 19: Pie chart with aquatic ecotoxicity potential divided into the process steps of the study.

13.2.3 Human Toxicity Potential

The human toxicity potential for the *Business as Usual* scenario is presented in the figures below (Figures 20 and 21). The total effects on human health were 0.0164 CTU_h/FU (Scenario I), 0.0114 CTU_h/FU (Scenario II) and 0.022 CTU_h/FU (Scenario III). Similarly to the EtP and as seen in Figure 21, almost all of the human toxicity comes from the extraction and processing & refining steps.

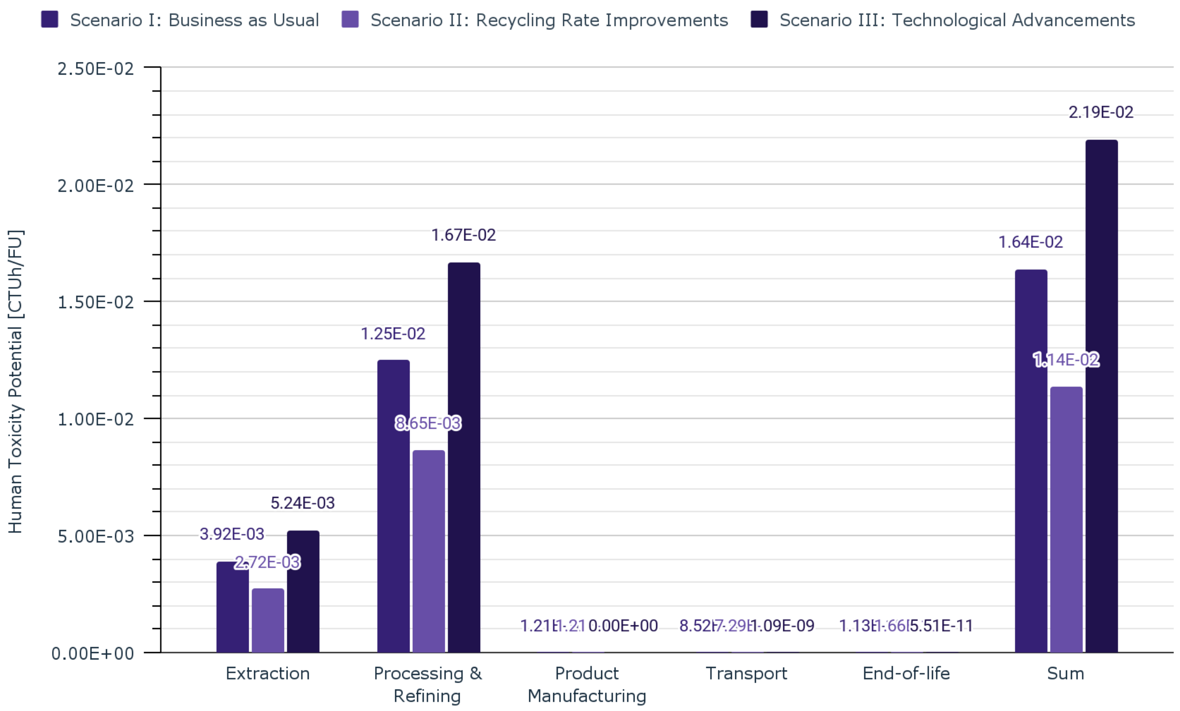


Figure 20: Human toxicity potential for each process step and scenario presented as CTU_h/FU.

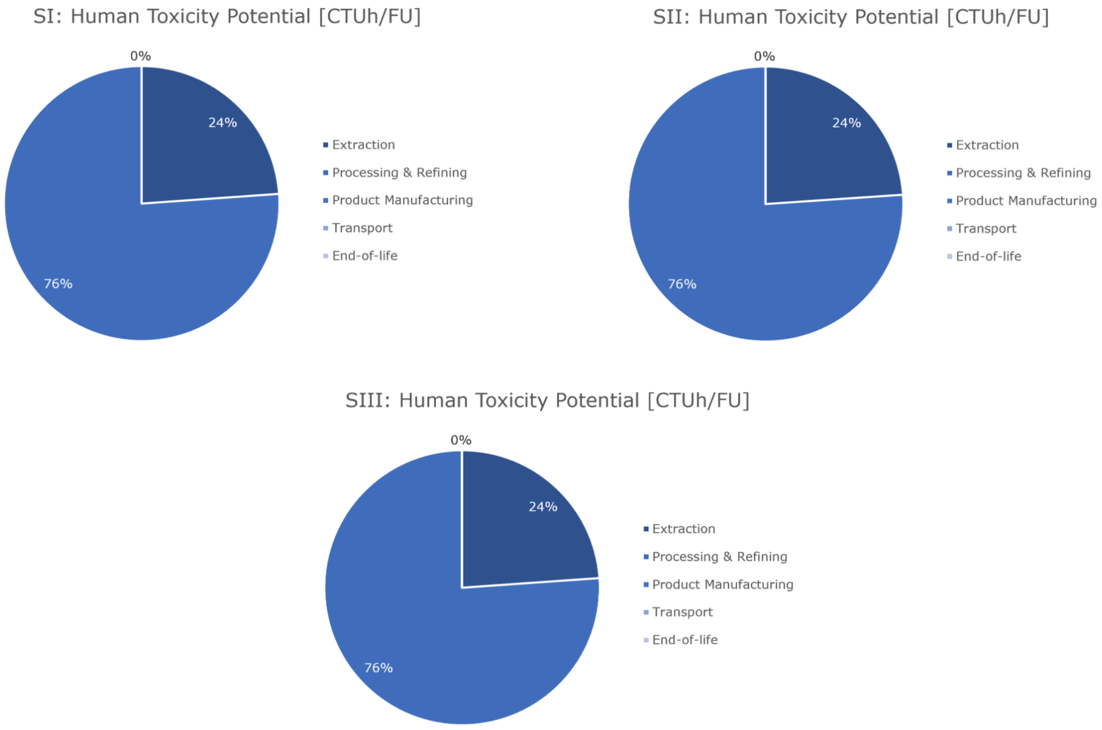


Figure 21: Pie chart with human toxicity potential divided into the process steps of the study.

13.2.4 Acidification Potential

The total acidification potential of a kilogram of cobalt used in LIB manufacturing is 0.0312 kg SO_2-eq for the *Business as Usual* scenario, 0.0275 kg SO_2-eq for the *Recycling Rate Improvements* scenario and 0.0123 kg SO_2-eq for the *Technological Advancements* scenario as seen in Figure 22 below. Regarding the most impactful steps, for Scenario I and II they are the product manufacturing and refining steps, whilst for Scenario III processing followed by refining caused the most acidifying emissions (Figure 23).

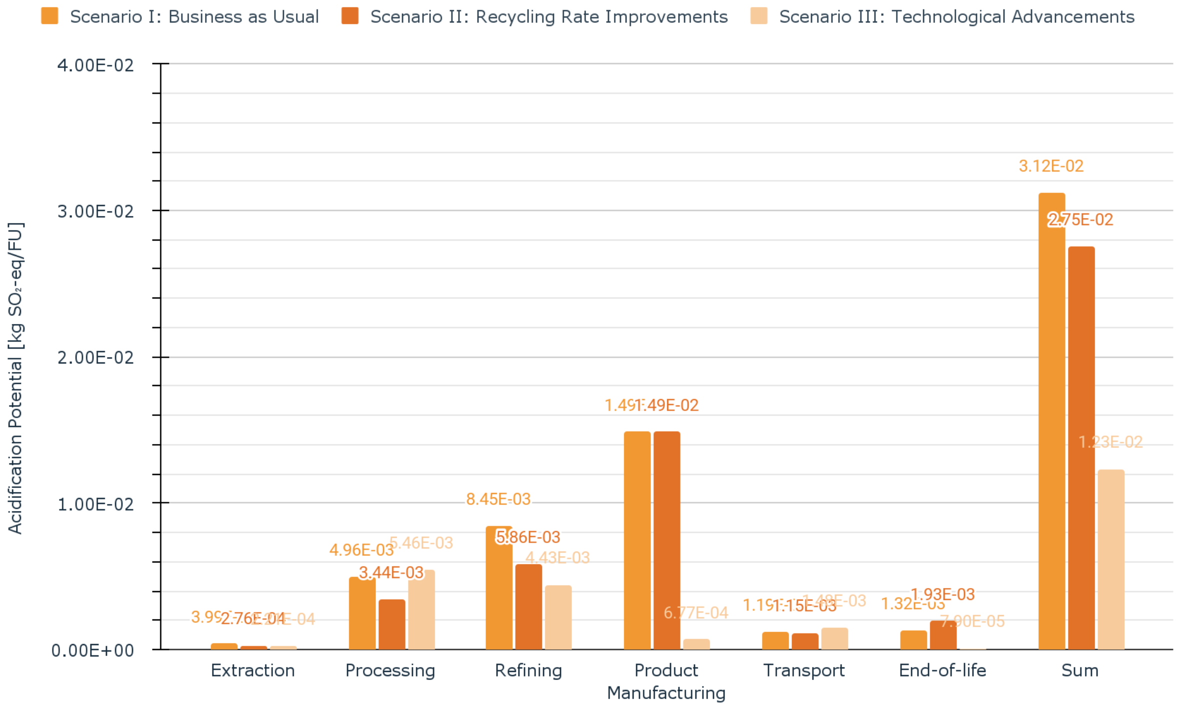


Figure 22: Acidification potential for each process step and scenario presented as kg SO_2-eq/FU.

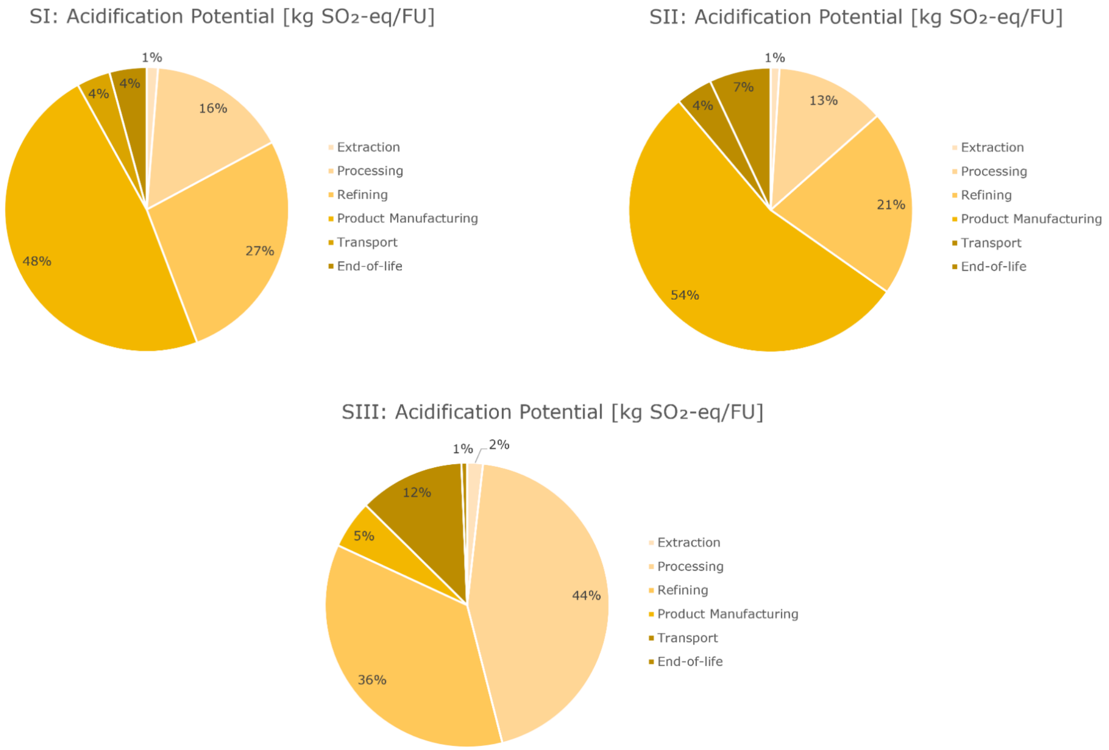


Figure 23: Pie chart with acidification potential divided into the process steps of the study.

13.2.5 Eutrophication Potential

For eutrophication potential, the sum of all eutrophic emissions per functional unit was 0.0024 kg PO_4^{-3}-eq/FU for *Business as Usual*, 0.0020 kg PO_4^{-3}-eq/FU for *Recycling Rate Improvements* and 0.0015 kg PO_4^{-3}-eq/FU for *Technological Advancements* as seen in Figure 24. For both Scenario I and II, the refining and product manufacturing steps dominate the eutrophic emissions, while for Scenario III the product manufacturing step stands for over 75 % of the total EP by itself (Figure 25).

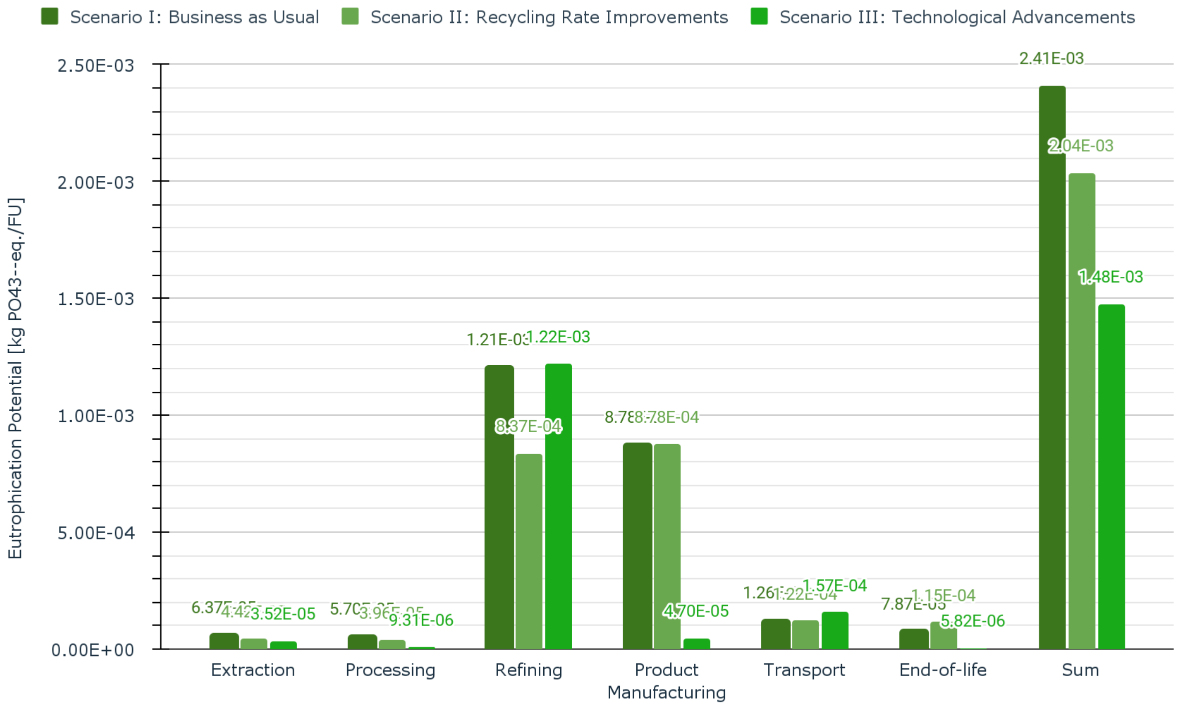


Figure 24: Eutrophication potential for each process step and scenario presented as kg PO_4^{-3}-eq/FU.

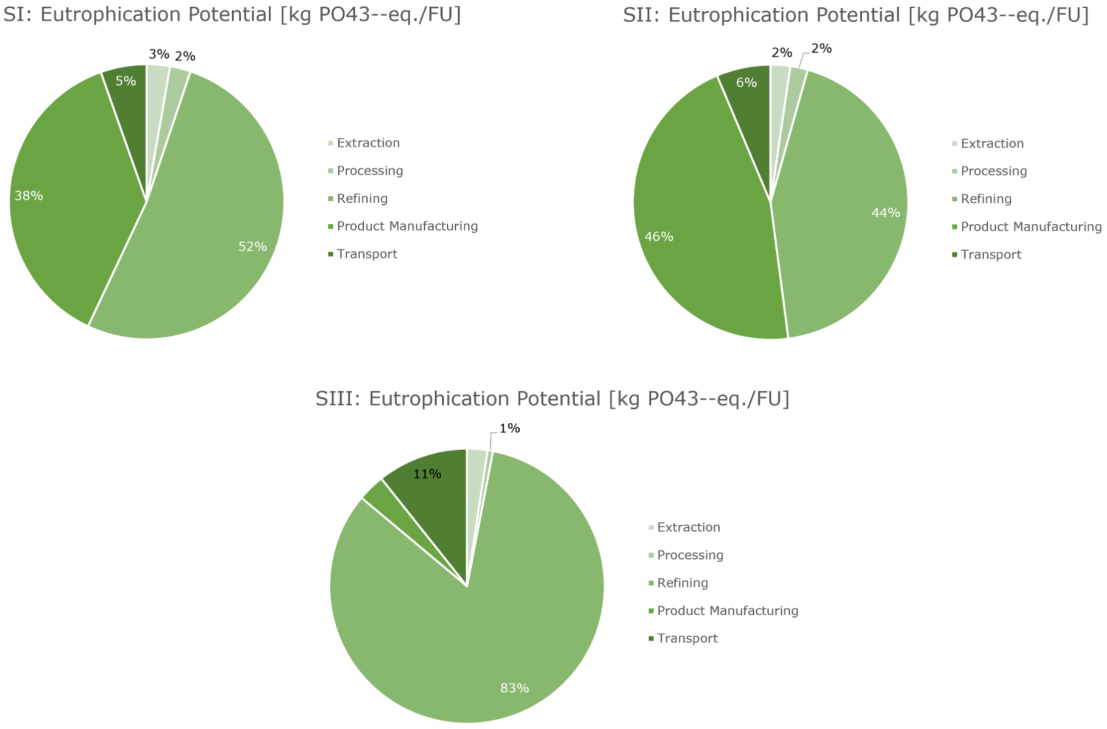


Figure 25: Pie chart with eutrophication potential divided into the process steps of the study.

13.3 Comparison

The sum of all environmental impact categories for each scenario are presented in Table 14 for comparison.

Table 14: Total effect for each EIC and scenario.

Environmental impact category	SI: Business as Usual	SII: Recycling Rate Improvements	SIII: Technological Advancements	Unit
Global Warming Potential	18.0	15.9	7.51	kg CO_2-eq /FU
Aquatic Ecotoxicity	16 100	11 100	21 500	CTU_e/FU
Human Toxicity	1.64E-02	1.14E-02	2.19E-02	CTU_h/FU
Acidification Potential	3.12E-02	2.75E-02	1.23E-02	kg SO_2-eq/FU
Eutrophication	2.41E-03	2.04E-03	1.48E-03	kg PO_4^{-3}-eq/FU

13.4 Sensitivity Analysis

All three scenarios assume that no shift will occur in the geographical distribution of the different lifetime stages of cobalt, i.e that China will still process 65 % of all cobalt used in LIBs in both 2030 and in 2050. This is however unlikely as both the US and the EU, two of the biggest consumers of LIBs, have signed separate agreements that include goals to reduce the amount of cobalt that isn't processed domestically. The EU's Critical Raw Materials Act was introduced on 16 March 2023 and had the explicit intention of facing the problems the EU faces in regards to the acquisition of critical raw materials. According to the act, the demand for rare earth metals will increase seven-fold in the EU by 2050 and, according to the EU, the heavy reliance on imports of these materials is detrimental to the EU's climate goals. Thus, the act proposes several benchmarks that must be met by 2030. Firstly, 10 % of the EUs demand for strategic raw materials (in 2030) must be supplied by the EU, secondly, 40 % of demand must be processed in the EU and thirdly, 15 % of demand must be recycled in the EU. Furthermore, no more than 65 % of the EUs annual consumption must come from a single country (European Commission, 2023). In 2022, the US signed the Inflation Reduction Act which included, among other things, tax credits for certain EVs. For an EV to be tax credit eligible it has to, after 31 December 2026, fulfill the criteria that at least 80 % of the total market value of all materials used in its battery are extracted and processed by either the US or any of its free trade partners (Trost and Dunn, 2023). As this report assumed that processing and refining took place in the same location all changes in geographical distribution applied to processing will be assumed to also apply to refining.

Both of these acts will, if followed, have a clear impact on the geographical distribution of cobalt extraction, processing and refining and, specifically, on China. The Critical Raw Materials Act will reduce the amount of extraction that is done outside of the EU but this goal (10 %) will have a much smaller effect than making sure that 40 % of processing & refining is done in the EU. Thus the effect will be larger on China than the DRC. Processing/refining is, as has been mentioned many times previously, mostly done in China and extraction is primarily in the DRC. The Inflation Reduction Act allows outside extraction and processing/refining to be performed by any of the US' free trade partners but these do not include China (Office of the United States Trade Representative, 2020). The Inflation Reduction Act will also most likely have a major impact on the DRC as it also aims to majorly reduce outside extraction and the DRC is not one of the US' free trade partners. Extraction of cobalt used in EVs from the US might instead be carried out by countries like Australia or Canada which are free trade partners.

Due to these acts it is very likely that the geographical distribution of several steps will change by 2050. In 2020 Europe covered approximately 22.5 % of global cobalt consumption whilst North America covered 17.7 % (Garside, 2021). By assuming these values correspond to EU and US consumption an approximate shift in geographical distribution can be calculated. 40 % of 22.5 % means that about 9 % of cobalt processing will shift to the EU, it will further all be said to shift from China. This processing & refining will be said to be divided evenly between Finland and Belgium (the two largest processors/refiners currently). 80 % of 17.7 % means that 14.1 % of processing will shift from China to the US or a US free trade partner. This processing & refining will be said to be distributed between the US, Australia and Japan but with a majority taking place in the US (current distributions will be said to be 1 % US, 1 % Japan and 2 % Australia). Consequently, by applying these assumptions, in 2050 41.9 % of processing & refining will take place in China, 14.5 % in Finland, 9.50 % in Belgium, 9.06 % in Australia, 8.06 % in the US and 8.06 % in Japan. Refining will be said to have the same distribution. The same calculations are done for extraction, with 10 % of 22.5 % meaning that 2.25 % of cobalt extraction will shift to the EU, this will be said to go from the DRC to Finland. 14.1 % of extraction will also go from the DRC to the US, Canada and Australia (the majority will be said to go to Australia as they have the biggest cobalt reserves). Current cobalt mining distribution can be seen in Figure 5**.** The geographical distribution of extraction will consequently be, 53.8 % in the DRC, 10.3 % in Australia, 5.63 % in Canada, 5.39 % in Indonesia (same as before), 4.80 % in Russia (same as before), 3.93 % in the US and 2.25 % in Finland. Recycling will also shift but only slightly, 3.38 % of China's recycling (15 % of 22.5 %) will be said to go to Europe. Recycling distributions will thus be 54.9 % in China, 31.9 % in Europe and still 6.67 % in Japan. As battery manufacturing is not covered by any of the acts its geographical distribution will be assumed to remain the same. The old and new geographical distributions following the sensitivity analysis are summarized in Table 15, Table 16 and Figure 26.

Table 15: Old and new geographical distribution of extraction as a result of the sensitivity analysis and the Critical Raw Materials Act and the Inflation Reduction Act.

Pre Sensitivity Analysis		After Sensitivity Analysis	
Country	**Percentage**	**Country**	**Percentage**
DRC	70.1	DRC	53.8
Indonesia	5.39	Australia	10.3
Russia	4.80	Canada	5.63
		Indonesia	5.39
		Russia	4.80
		USA	3.93
		Finland	2.25

Table 16: Old and new geographical distribution of processing and refining as a result of sensitivity analysis and the Critical Raw Materials Act and the Inflation Reduction Act.

Pre Sensitivity Analysis		After Sensitivity Analysis	
Country	**Percentage**	**Country**	**Percentage**
China	65.0	China	41.9
Finland	10.0	Finland	14.5
Belgium	5.00	Belgium	9.50
		Australia	9.06
		USA	8.06
		Japan	8.06

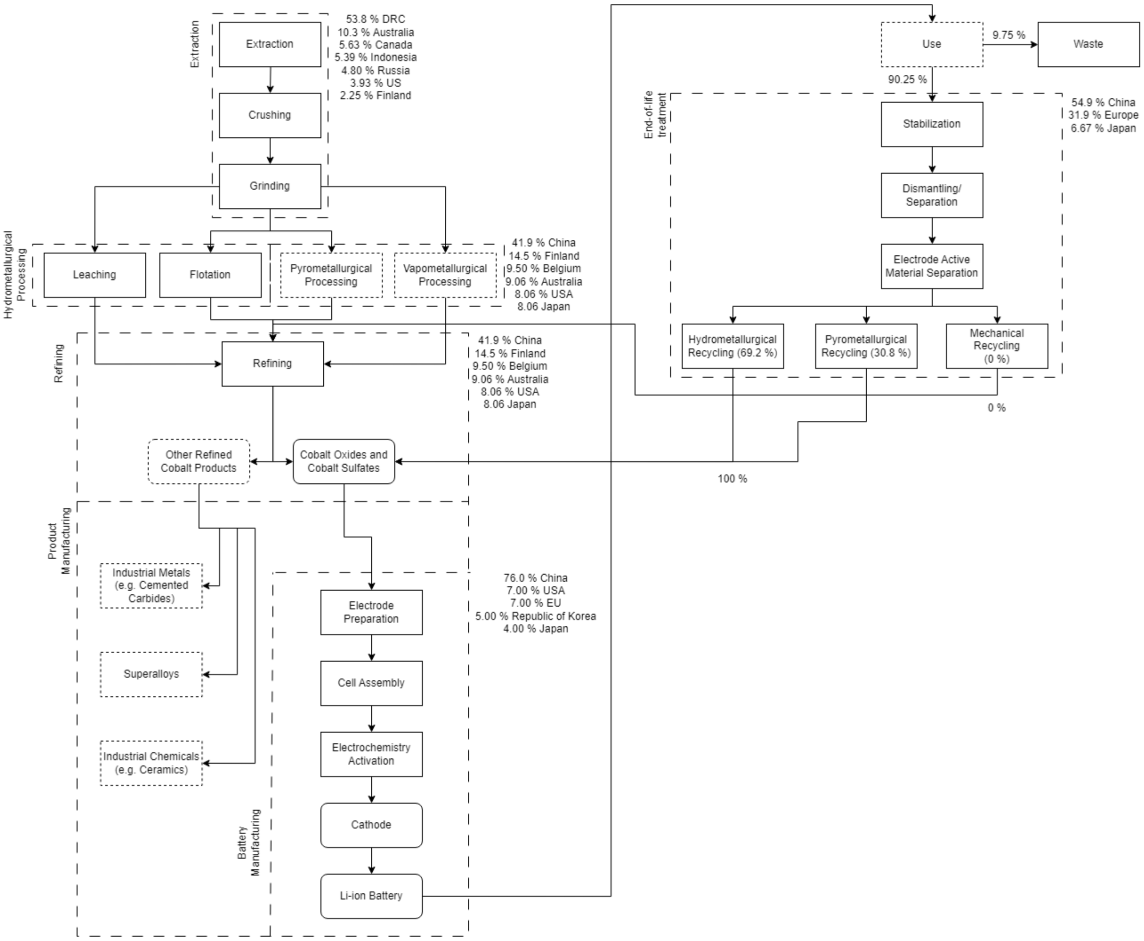


Figure 26: Flow chart of cobalt after sensitivity analysis has been applied. Geographical distribution of extraction, processing, refining and recycling have been altered.

13.4.1 Sensitivity Analysis Results

The following figures show the results of the sensitivity analysis compared to previous results. All three scenarios in the sensitivity analysis have utilized the altered geographical distributions that were laid out in the previous section. The chart below shows the altered GWP compared to previous results. The sum is lower in the first two scenarios, 17.5 CO_2-eq/FU and 15.6 CO_2-eq/FU respectively compared to 18.0 CO_2-eq/FU and 15.9 CO_2-eq/FU respectively. Scenario III, on the other hand, resulted in a higher sum of GWP after the sensitivity analysis, with 7.62 CO_2-eq/FU compared to the original 7.51 CO_2-eq/FU. The results are summarized in Figure 27.

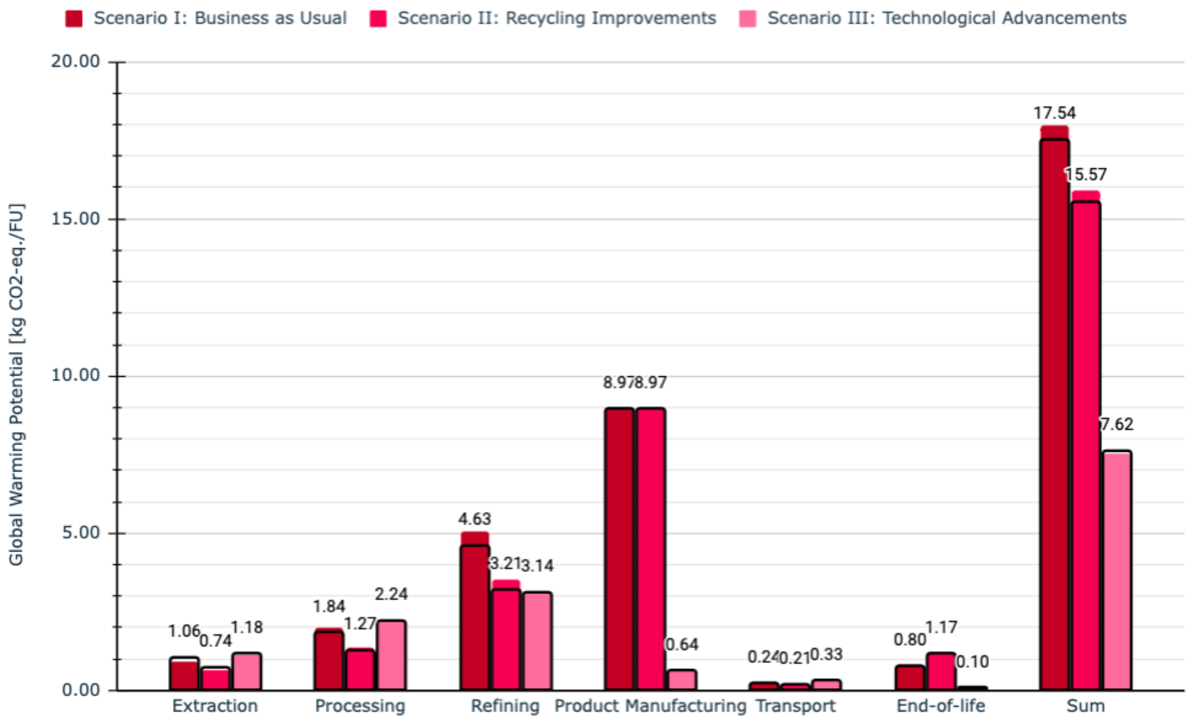


Figure 27: GWP with original geographical distributions as well as altered distributions used in sensitivity analysis. Colored columns show original results whilst transparent columns show sensitivity analysis results. Data labels represent results of the sensitivity analysis.

The acidification potential changes similarly to GWP. The AP in scenario I and II both decrease to 2.95E-02 kg SO_2-eq/FU and 2.64E-02 kg SO_2-eq/FU from 3.12E-02 kg SO_2-eq/FU and 2.75E-02 kg SO_2-eq/FU respectively. Scenario III, like with GWP, shows an increase with the sensitivity analysis but only a very slight one, with the sum going from 1.23E-02 kg SO_2-eq/FU to 1.24E-02 kg SO_2-eq/FU. The results are summarized in Figure 28.

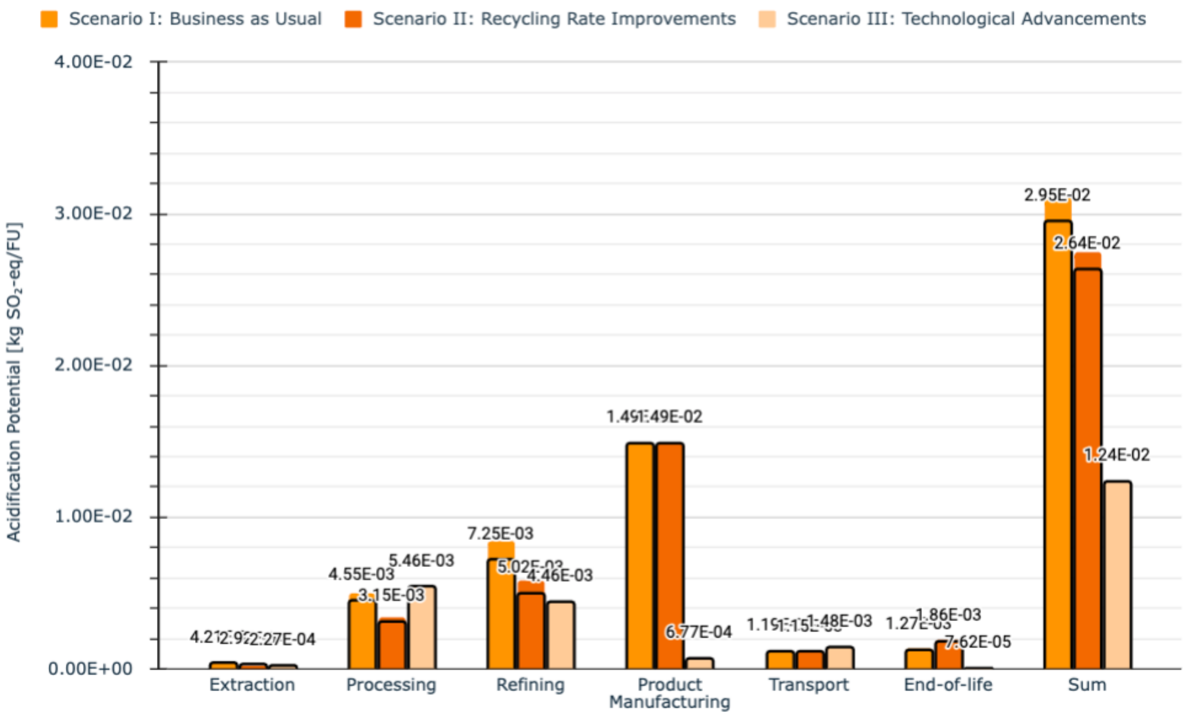


Figure 28: Acidification potential with original geographical distributions as well as altered distributions used in sensitivity analysis. Colored columns show original results whilst transparent columns show sensitivity analysis results. Data labels represent results of the sensitivity analysis.

The changes in eutrophication potential are very similar to those in acidification potential. The sum of EP consequently decreases in the first two scenarios, from 2.41E-03 PO_4^{3-}–eq/FU and 2.04E-03 PO_4^{3-}–eq/FU to 2.33 PO_4^{3-}–eq/FU and 1.98 PO_4^{3-}–eq/FU respectively. Scenario III once again shows a very slight increase, going from 1.48E-03 PO_4^{3-}–eq/FU to 1.49 PO_4^{3-}–eq/FU. The results are summarized in Figure 29.

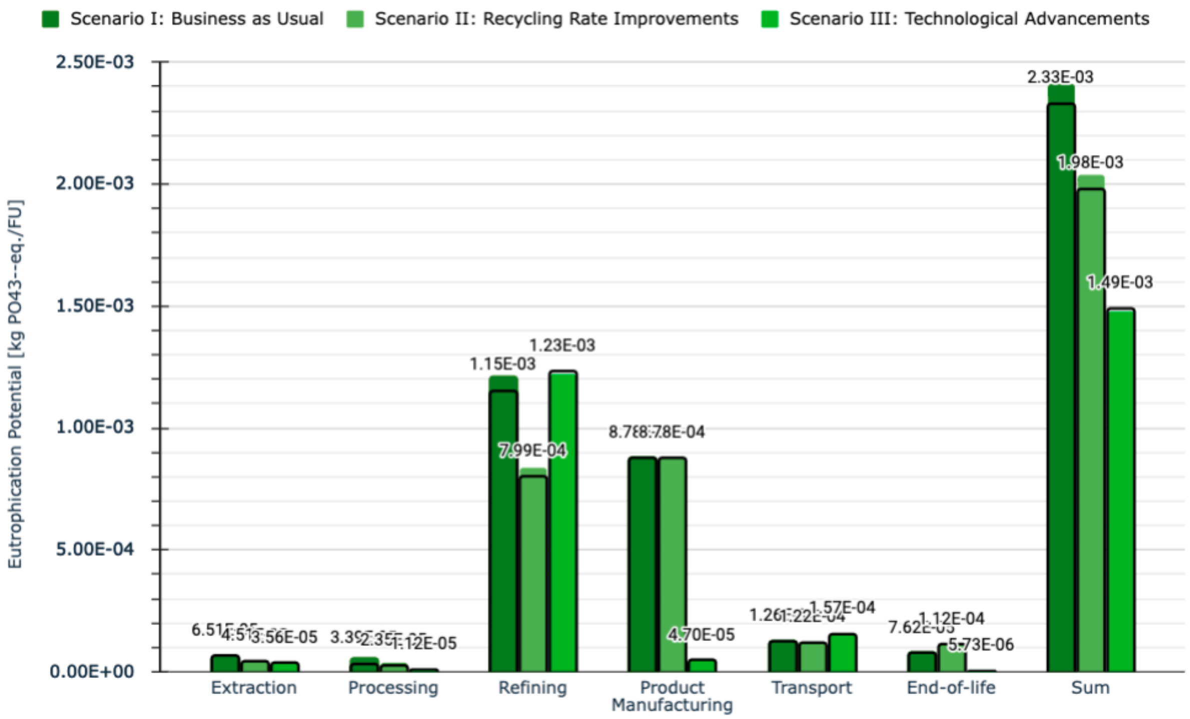


Figure 29: Eutrophication potential with original geographical distributions as well as altered distributions used in sensitivity analysis. Colored columns show original results whilst transparent columns show sensitivity analysis results. Data labels represent results of the sensitivity analysis.

14 Discussion

The results gathered in the report were discussed in this section. It covers how they relate to both scarcity and environmental effects. A sensitivity analysis was also carried out and several concepts that could have large effects on cobalt were discussed, such as second life of batteries and future extraction techniques. Assumptions, sources of errors and possible improvements were also covered.

14.1 Scarcity

14.1.1 Scenario I: Business as Usual

As can be seen in the results, the first scenario caused the highest annual use of virgin cobalt (635 kilotonnes by 2050) as well as the most total primary cobalt use (10.8 million tonnes). This was expected as Scenario I included no technological advancements nor improvements to recycling. The value of 10.8 million tonnes can be compared to the current total terrestrial cobalt resources of about 25 million tonnes (as mentioned under *Mineralogy of Cobalt)*, seeing that just LIBs, even though they represent the largest fraction of cobalt usage (80 % in 2050), would use up about 43.2 % of the Earth's cobalt resources available for conventional mining by 2050. As such, no *immediate* risk for scarcity can be seen from a resource availability perspective. Whilst there is no immediate risk of running out of cobalt resources, resources are, by their definition, not currently available commercially or geographically. Current reserves are estimated to be about 8.3 million tonnes which means reserves have to be expanded to keep up with the demand of this scenario. Additionally, this does not take into account the fact that the cost of extracting cobalt increases as more accessible ore seams are mined, effectively leading to reserves becoming less economically viable. The model does not consider large increases of cobalt usage in other sectors than LIBs either, which would naturally also affect cobalt availability/scarcity. It is also clear that while depletion of cobalt does not, according to this projection, seem to occur in the nearest 30 years, it is a real possibility in the following years as the total primary supply for this scenario is far larger than for Scenario II and III (Figure 15). Scenario I is also based on some rather drastic assumptions such as stagnation of both recycling efforts and technology of lithium ion batteries and is as such not particularly realistic. It is however an indication that the current use of cobalt is unsustainable in the long term.

14.1.2 Scenario II: Recycling Rate Improvements

Scenario II resulted in a significant reduction in cobalt usage as compared to Scenario I, 8.30 million tonnes vs. 10.8 million tonnes. This was, logically, a result of the highly increased recycling rate which meant that 90 % of all cobalt in lithium-ion batteries that entered the end-of-life stage was usable in the production of new LIBs. As LIBs have a long lifetime (in this scenario said to be 10 years) the effective recycling rate, i.e how much cobalt actually comes from secondary sources as opposed to primary sources, never reaches 90 %. By 2050 the share of secondary supply is 58.1 %, which consequently means that significant levels of mining still have to take place. The shares will, however, move towards 90/10 as time passes. The reason for this is the increasing amounts of cobalt in use and subsequently in the recycling stage as new cobalt enters into the stream and already recycled cobalt reenters. This level of usage, as it remains significantly lower than total deposit reserves, is more sustainable than Scenario I. It would take longer for cobalt to run out following this scenario but, as long as cobalt demand keeps increasing, would happen eventually. As with Scenario I this scenario would also require resources becoming reserves but to a lesser extent. Scenario II is based on several large assumptions, mainly that battery technology remains stagnant from today up until 2050 but additionally that global recycling rates can reach as high as 90.25 %. Realistically cobalt usage in LIBs would most likely decrease (as in Scenario III) along with increased recycling. It does, however, showcase what a large effect improving the recycling of cobalt in LIBs would have on reducing the risks of cobalt scarcity.

14.1.3 Scenario III: Technological Advancements

Scenario III forecasted the lowest overall cobalt demand out of the three scenarios as it was the only one to incorporate reduced cobalt usage in batteries. As such it had far lower cobalt usage than both Scenario I and II, with only 3.68 million tonnes of primary cobalt used by 2050. It also, despite not incorporating any improvements in recycling, ended up with a lower total primary supply than Scenario II. The decreased demand therefore had a larger impact on how much cobalt had to be mined than increasing the recycling rate had. Scenario III can thus be said to be drastically better than the other two scenarios (when discussing scarcity) as it both resulted in lower overall cobalt demand as well as lower primary supply demand. It was the only scenario that didn’t exceed current cobalt reserves and as such didn’t require that any cobalt resources would become reserves. As with Scenario II, this Scenario is based on some large assumptions, here mainly that recycling stagnates and does not improve.

Between 2021 and 2030 Scenario III actually shows a reduction in overall cobalt demand, from 120 kilotonnes to 107 kilotonnes. This is a result of the reduction in the amount of cobalt present in each LIB which is enough to lower the entire demand of cobalt despite the fact the demand for LIBs is still assumed to increase in the same period. As a result of this, secondary supply ended up being lower in 2050 than in 2030 in Scenario III. This was due to the fact that Scenario III assumed a doubling of LIB lifetime in 2030 which, consequently, meant that LIBs produced this year would not enter the end-of-life stage until 20 years in the future (2050). Less cobalt will consequently be available for recycling in 2050 than in 2030, as overall demand was lower in 2030 than in 2021, and as the recycling rate remains the same in this scenario the amount of secondary cobalt decreases.

14.1.4 Cobalt as a Byproduct

As was mentioned earlier on, cobalt is most often mined as a byproduct of copper and nickel. This report has not taken this into consideration when estimating the risks of scarcity and instead assumed that demand for cobalt was separate from the demand for e.g. nickel and copper. Would the demand for nickel and copper suddenly be reduced, perhaps as a result of reduced usage of these metals in a certain product, the access to cobalt would be reduced as well. There is thus no guarantee that cobalt scarcity will be avoided just because cobalt reserves are large. However, this might change in the future. If the demand were to become big enough, extraction could begin to be carried out with the sole purpose of gathering cobalt and, consequently, access to cobalt would no longer be constrained by the demand for other metals.

14.2 Environmental Impacts

14.2.1 Global Warming Potential

Figure 16 clearly shows that Scenario I has the highest GWP out of the three scenarios, with a sum of 18.0 kg CO_2-eq/FU as opposed to 15.9 kg CO_2-eq/FU for Scenario II and 7.51 kg CO_2-eq/FU for Scenario III. The biggest contributor to GWP in the first two scenarios is, by a significant margin, product manufacturing. This is what causes the very obvious difference between Scenario I & II and Scenario III. Product manufacturing is, today, primarily carried out in China where the electricity mix heavily leans towards fossil fuels with as much as 63.5 % being coal. Employing coal power plants brings significant GWP and as Scenario II assumes the same amount of product manufacturing as Scenario I (as recycling only affects earlier steps), these two are similarly affected. Scenario III, on the other hand, assumes that the electrical mix of China will undergo major changes by the year 2050, with renewable sources becoming the major source of power and coal getting reduced to only 7 %. This consequently means that product manufacturing will have a much smaller impact on the GWP in Scenario III. The reason Scenario I has a higher GWP is that Scenario II, as a result of a much higher fraction of secondary cobalt, utilizes less processing and refining which are the two steps with the highest GWP after product manufacturing. Logically, the highest impact from the end-of-life stage comes from Scenario II as this assumes the most amount of recycling (highest fraction of secondary cobalt). Overall impact from this stage is still low, showing that recycling is not a particularly large contributor of GWP.

It should also be mentioned that Scenario III has the highest fraction of primary cobalt as opposed to secondary cobalt out of the three scenarios. But, as was mentioned earlier, does assume a different electrical mix which explains why the GWP of the refining stage is still smaller in Scenario III. The GWP impact of the extraction step is, despite this, almost as high in Scenario III as in Scenario I and higher than in Scenario II. Furthermore, in the processing step Scenario III actually has the highest impact on GWP. This is due to the fact that not all GWP comes from electricity usage. Instead, a lot of GWP can be sourced to chemical usage in these steps and, as Scenario III has the highest primary cobalt fraction, means that this scenario results in the highest amount of chemical usage.

14.2.2 Aquatic Ecotoxicity Potential

Essentially all aquatic ecotoxicity potential can be traced back to the extraction stage and the processing & refining stage with extraction being especially dominant. The reason why was mentioned in Appendix G but, in brief, is due to the high amount of cobalt that gets lost during mining. It should be mentioned that all of these stages occur before the battery manufacturing stage and thus that secondary cobalt will essentially provide zero impact on EtP. Scenario III does not assume that less cobalt will be lost during mining in the future and as it has the highest fraction of primary cobalt ends up with the highest aquatic ecotoxicity potential per functional unit. The same is true for processing & refining, as Scenario III has the most primary cobalt it will thus require the most processing & refining. The inverse is true for Scenario II which has the lowest fraction of primary cobalt and consequently the lowest EtP out of the three scenarios.

14.2.3 Human Toxicity Potential

The results for human toxicity potential are similar to aquatic ecotoxicity in that they all can be traced to primary cobalt. Consequently, Scenario III, with the highest primary cobalt fraction, has the highest HTP and Scenario II, with the lowest primary cobalt fraction, the lowest HTP. Contrary to EtP, processing & refining has a larger overall impact on HTP than extraction. This is potentially due to the fact that the toxic effects of cobalt are more severe for freshwater organisms than humans. Something that is important to note regarding the HTP (and also the AtP) is that increasing the recycling rate is one of the most effective ways of reducing toxicity as almost all of it arises from the mining, processing and refining steps. Increased recycling is thus paramount to alleviate the detrimental health effects of the early stages in the cobalt life cycle as seen in, e.g., the DRC.

14.2.4 Acidification Potential

The same principle as in GWP applies to acidification potential. The main source of acidification potential is battery manufacturing due to high fossil fuel usage which means Scenario I and II both have higher acidification potential than Scenario III. The difference between I and II here also comes from the lower fraction of primary cobalt in Scenario II. A substantial amount of the AP also arises directly from processing steps like leaching and/or flotation rather than electricity use.

14.2.5 Eutrophication Potential

Regarding eutrophication potential, battery manufacturing, like for GWP and AP, was the largest contributor. As this is primarily caused by fossil fuel usage, a large decrease can also be seen when comparing Scenario I and II with III, with a new electricity mix in China causing major reductions. The overall eutrophication potential is, however, more similar between the three scenarios than it was for GWP and acidification owing to the fact that refining also has a significant impact. Scenario III furthermore has a larger eutrophication impact in the refining stage than Scenario II does and only a slightly lower impact than Scenario I. This consequently means that the main source of eutrophication potential in the refining stage is not fossil fuel usage. Instead other sources like steam stripping of excess ammonia have more significant impacts.

14.3 Sensitivity Analysis

The sensitivity analysis utilized the EU's Critical Raw Materials Act as well the US' Inflation Reduction Act in order to examine what changes in geographical distribution would have on the results. By applying these acts and assuming they will be fully achieved the distribution of extraction, processing, refining and recycling could be altered. Consequently the amount of cobalt that was extracted in the DRC and the amount of cobalt that was processed, refined and recycled in China were reduced. Both acts had the clear aim of moving these steps away from the DRC and China to the EU and the US. The environmental effects of applying these acts were, however, not as straightforward. In the first two scenarios the sensitivity analysis resulted in lowering of GWP, AP and EP. The reason for this was that capabilities were moved from fossil-intensive China to places with more renewable energy sources, such as Finland and Belgium, causing less GWP, AP and EP from mainly the processing stage. Some capabilities were also moved to Australia, USA and Japan which, while better than China, still employ significant amounts of fossil fuels, making the reduction slightly less noticeable. It is, however, important to mention that the sensitivity analysis actually resulted in an increased GWP, AP and EP in the extraction stage. This was due to the fact that the DRC actually has a less CO_2-intensive electricity mix than all the countries that were assumed to fill in their reduced capabilities, i.e. Australia, Canada, Indonesia, Russia, USA and Finland.

Scenario III differed from Scenario I and II. The sensitivity analysis actually caused a slight increase in GWP, AP and EP as a direct result of changes in electricity mix in the different countries. The most relevant country in this discussion was China. Due to China's highly ambitious goals in regards to reducing their fossil fuel usage by 2050 their carbon intensity (assuming they reach their goals) will actually end up being lower than the US, Russia and Indonesia. Consequently, by moving capabilities from China to the US, Russia and Indonesia in Scenario III, the GWP, AP and EP will increase. However, capabilities moving from China to Finland, Belgium or Japan will still have a positive environmental impact (as they will have lower CO_2-intensity) but by looking at the results, the altered geographical distribution is seen to cause an overall increase in GWP, AP and EP in the processing and refining stages, meaning that moving capabilities away from China has more of a negative environmental impact in this case than moving some to Finland, Belgium and Japan. The GWP was increased as a result of the sensitivity analysis in the extraction step as well, which could be attributed to the fact that the DRC's 2050 electricity mix had a lower CO_2-intensity than for instance Australia, USA and Indonesia. GWP, AP and EP also increased in the extraction step, though only slightly as much of these emissions are not connected to electricity usage.

14.4 Second Life

A concept that is not covered by this study, but that could affect the results rather drastically, is second life. Second life for batteries proposes that spent EV batteries, e.g. LIBs, instead of entering the waste stream to be recycled, are repurposed as energy storage for the electrical grid, an application that has lower quality standards and thus suitable for the slightly deteriorated Li-ion batteries. The technical and economical viability of LIB second life are somewhat uncertain, but one study states that a lithium ion battery could have a second lifetime of 10 years, leading to lower costs and a reduction of about 56 % of CO_2-emissions compared to the production of a new battery (Martinez-Laserna et al., 2018). Although these predictions might not prove perfectly accurate, they show a venue for both environmental and monetary gain, indicating that second life will probably be applied to at least a portion of spent EV LIBs in the future. If that were to be applied to any of the three scenarios, suitably either Scenario II and/or III, the lifetime for cobalt would increase. That, in turn, would lead to less cobalt available for recycling in the short term, causing more primary cobalt to be used, and thus more negative environmental effects. This is similar to what was seen in Scenario III where battery lifetime also increased. However, it is worth considering that the alternative to second life, manufacturing new batteries for grid storage, could be worse for the environment. Consequently, the extent to which second life is implemented has to be weighed against both cobalt availability and environmental gain/loss.

14.5 Additional Sources of Secondary Cobalt

When estimating secondary supply this report has gone under the assumption that the only available source of cobalt is LIBs. This was done to facilitate calculations and to rein in the scope of the study, using cobalt from all sources would have required far more work. But, realistically, secondary cobalt could come from essentially all products that utilize cobalt, such as cemented carbides and superalloys (as long as they are recyclable). LIBs cover about 65 % of the market share of cobalt, which means a lot of cobalt not in LIBs is in circulation. This would consequently mean that more cobalt was available for recycling and that a larger amount and fraction of secondary cobalt would be possible. This is especially relevant for Scenario II (but would affect all scenarios). Here, adding an additional source of cobalt could mean that the 90 % recycling rate could potentially be reached at an earlier stage. Taking cobalt from other products and turning it into LIBs could, however, hurt these products as it will reduce their individual secondary supply.

14.6 Future Extraction/Processing Techniques

As mentioned earlier in this report, there are multiple extraction methods and at least one processing technique relevant for cobalt that are currently in the research or early testing stages. Due to the uncertain future of these new technologies, they were not included in any of the scenarios, but at least one, if not several, of them could reasonably take over significant market shares within the foreseeable future.

14.6.1 Phytomining

Phytomining is, as a whole, limited since it really only is worth the time in certain places, those being areas heavily contaminated with cobalt (containing high cobalt concentrations, e.g. the Katanga Copper Belt). But it does, at the same time, also come with significant benefits. As it involves gathering cobalt from the ground it, as well as being a way to gather cobalt, helps clean up the contaminated ground making it one of the few cobalt gathering methods that can be considered environmentally beneficial. Additionally, energy recovery is possible when burning the plants making the process cheaper (Earl et al., 2022; Lange et al., 2017).

Phytomining could alleviate some concerns related to scarcity as it enables recovery of cobalt that would otherwise have been lost. The overall potential is, however, quite low so its benefits in this area can be said to be limited. As mentioned above it could, despite this, be quite useful when reducing the environmental impact of the extraction of cobalt. The extraction step causes significant aquatic and human toxicity potential as a result of the release of cobalt into nature. Being able to recover this cobalt would thus be highly beneficial and could help greatly reduce the toxicity potential of cobalt. This could be especially true for Katanga as it faces such severe environmental effects from the mining industry.

14.6.2 Deep Sea Mining

The benefits of deep sea mining were discussed previously in this report and it could, if properly applied, greatly increase worldwide cobalt supply. The highest estimate of submarine cobalt deposits is as high as 120 million tonnes, Current estimates of terrestrial deposits is about 25 million tonnes which means that deep sea mining could, potentially, quadruple total deposits. Whilst this might make it a very lucrative technology for many states and corporations, deep sea mining also carries with it significant environmental risks.

The deep seafloor is still poorly understood. It is difficult to know with certainty exactly what the effects of deep sea mining will be as we lack a lot of information about the ecosystems and biodiversity of the benthic ocean environment. Many species that inhabit these areas are uniquely adapted to the specific conditions that prevail here, such as low temperatures, lack of sunlight and extremely high pressure. Digging and exploring the seafloor can have significant effects on habitats and lead to both fragmentation and destruction. This, combined with the fact that the native species will not be able to survive elsewhere, means that deep sea mining could have major adverse effects. Additionally, knowledge on the number of species is lacking which means that more species could be harmed than initially assumed. Another concern with deep sea mining is that it can cause the creation of large plumes of suspended particles. When operating on the seafloor a lot of sediment can be stirred up which can then be dispersed far distances, especially as mining ships moored at the surface displace large amounts of water. These particles can directly affect animals by covering and smothering them, impair their ability to see and be especially harmful to filter-feeders. The operation will also be very invasive, emitting large amounts of light pollution, noise and vibrations which can negatively affect many species but especially those that heavily rely on communication, such as whales. Finally, operating heavy machinery and constructing infrastructure underwater comes with the risk of potentially, in case of an accident, releasing dangerous and toxic products, for instance fuel, metals and other electronics (International Union for Conservation of Nature, 2022).

Applying deep sea mining to any of the scenarios studied in this report would, consequently, have significant impacts on aquatic ecotoxicity. It could, furthermore, have major impacts on other categories like GWP and AP, as heavy machinery will have to be transported long distances (to the middle of the ocean) and will have to be run in adverse conditions. Deep sea mining will, in all likelihood, be applied in the near future as technology, supply and willingness exist (as evidenced by the many projects in place). It will thus be important to research exactly what the environmental effects will be, especially as the deep sea environment is so unique and easily disturbed.

14.6.3 Asteroid Mining

Asteroid mining is probably the least likely future extraction technique to have a relevant impact on cobalt supply within the analyzed time period as the technology is furthest from ready for large-scale, if any, use. Even though there is a clear economic incentive for asteroid mining, there could be other benefits as well. Asteroid mining would most likely partially supplant the need for terrestrial mining and as such reduce the release of toxic emissions and acids caused by in-ground mining. Some social benefits could also transpire from asteroid mining as it would reduce undesirable practices like child labor which is not uncommon in e.g. the DRC today. It is however worth noting that the large influx of raw materials would cause devaluation of formerly valuable materials like cobalt. As for the cobalt example, this would have detrimental effects on the whole economy of the DRC, raising concerns that these celestial resources would especially hurt developing countries. As such, the socioeconomic impacts of asteroid mining and how to alleviate them should definitely be taken into consideration (Yarlagadda, 2022).

The environmental effects of asteroid mining are, beyond the removal of the effects of currently extracted cobalt on Earth, naturally very difficult to estimate. The reduced toxic, acidic and eutrophic emissions on Earth would definitely have positive environmental effects locally, but new sources of emissions such as rocket fuel would arise, leaving, e.g., the GWP of an asteroid mining scenario uncertain. From an environmental perspective, comparing terrestrial and celestial cobalt might come down to a choice between environmental impact categories, which would require significant scientific support. In regards to cobalt scarcity, asteroid mining could be said to "solve" this problem as the solar system would provide near-inexhaustible amounts of resources. It is however important to note that whilst asteroid mining could provide almost infinite cobalt, it would only alleviate cobalt scarcity and not affect the sustainability of any steps other than extraction. As such, it would still be important to recycle used cobalt to reduce environmental effects and adhere closer to the concept of circular economy.

14.6.4 Bioleaching

As mentioned earlier, bioleaching is a possible hydrometallurgical process to apply to the end-of-life step to reduce costs, energy use and environmental burden. Using biological organisms to produce the needed acids and other chemicals as well as degrading cobalt-containing spent LIBs has the environmental benefit of not having to chemically synthesize the leaching chemicals as well as reduced emissions of toxic/acidic gasses and chemicals (Erüst et al., 2013). As such, it is very probable that using bioleaching would be preferable to conventional leaching when the technology is mature. Worth noting however, is that bioleaching for merely the end-of-life stage would have very limited positive effects as only a small portion of the environmental effects come from this stage. Therefore, for bioleaching to have an appreciable effect on the sum of the environmental impact categories, it has to be applied to the processing of ores as well as spent LIBs. Some studies have been conducted covering bioleaching for cobalt ores, with promising results, but the increased time required for bioleaching is a roadblock. A realization of bioleaching of ores would however have a significant impact on energy use, GHG emissions and acid consumption (Saim and Darteh, 2023).

14.7 Assumptions and Possible Improvements

Tables 8, 10 and 13 outline the largest assumptions that were made to facilitate calculations in each process step and scenario. These assumptions, logically, had significant effects on the results and would, if done differently, change the results drastically. All assumptions made in this report have been conservative, i.e. made with the intention of not diminishing any results. Consequently, the results reported were intended to present the worst case possible. Certain assumptions had larger effects on some EIA categories than others. The 7 % loss rate from the extraction step had, for instance, a significant impact on the toxicity categories. If the loss rate had been higher the toxicity would have increased, both due to the fact that more cobalt would enter the surrounding environment and that more extraction would have taken place.

Beyond changing the assumptions of the study, there are multiple ways the study could be altered. One major demarcation of this report was the fact that it only covers cobalt from and to be used for Li-ion batteries. If the analysis would have covered industrial metals, superalloys, and industrial chemicals as well as LIBs, it would have naturally been more extensive and more complete conclusions could have been drawn regarding cobalt scarcity. Another part of the study that could have been improved is the calculation of the results for the environmental impact analysis. These results were calculated using Excel, Google Sheets, UseTOX or based on other LCA studies, rather than using a dedicated LCA software, which would have made the results more robust. Finally, the *Technological Advancements* scenario does not include any direct technological improvements of e.g. machinery for the processing, refining and end-of-life steps.

It is reasonable to assume that at least one of these steps would improve in other aspects than electricity mix and that further study of prospective technologies and techniques in these areas would improve this scenario. Another important parameter to mention is the fact that allocation has been done solely based on mass throughout the report, for instance during the extraction and transport steps. Would the allocation instead have been economical the results might have looked very different. This is not necessarily an improvement but is important to mention.

14.8 Our Contributions and Future Areas of Adjacent Studies

Reports of this nature have been done previously, mostly with the intention of determining and measuring scarcity. Thus, most similar studies have not focused on the environmental impacts of future cobalt use (Watari et al., 2020). This report has aimed to fill this lacuna which it can be said to, at least partially, have done. By formulating three scenarios and investigating these from both a scarcity and EIA perspective, insight has been gained into both the risks of cobalt depletion and what environmental effects could possibly be expected in regards to how cobalt usage develops over time. One report from Nature found that cobalt scarcity was a larger issue than this report, with scarcity problems being predicted for all scenarios (Zeng et al., 2022a). The reason for this was that Zeng's report incorporated the feasibility of upscaling mining operations to cover the increased cobalt demand and found it lacking. This study instead assumed cobalt extraction to always be able to meet demand, explaining the disparities.

The future extraction/processing techniques brought up in the discussion have rather uncertain futures. An analysis of which processes could enter full-scale use and when that would occur, would be instrumental in determining the future of cobalt. In addition to this, a comparative analysis of environmental effects of conventional mining, phytomining, deep sea mining and asteroid mining would indicate which path to take for a more sustainable future. Another consideration which has not been included to a large extent in this report is the ore grade. As higher quality reserves are depleted, mining operations might shift to less cobalt-rich ore leading to additional adverse environmental effects. Investigating how this would affect the scenarios developed in this report is thus of interest.

Cobalt supply is, as mentioned earlier, highly dependent on demand for copper and nickel as it is almost always mined as a byproduct. This has not been a major part of this study but is naturally very important and a study covering this dependency would bring some clarity to the area. Investigating future copper and nickel demand could give indications of these metals' roles as constraints potentially causing cobalt scarcity.

Scenario III solely looks at the fact that the amount of cobalt is reduced in each LIB which, logically, means that the environmental impact of cobalt is greatly reduced. What could be further studied is thus what materials could potentially be used to replace cobalt in these batteries, and what the environmental effects this would have. This would require a study with the goal of estimating the environmental impact of an LIB, not a singular metal, and is thus separate from this study. It could, however, give valuable insight into LIBs.

Another area not brought up in the report is the concept of cobalt free batteries. Much research has been made in this realm due to many of the reasons mentioned throughout this report, e.g. the environmental effects of cobalt extraction and its limited supply. Issues with LIBs that do not include cobalt generally concern rapid capacity decay but researchers have been able to remedy this (Jia et al., 2021). It consequently seems likely that cobalt free batteries will enter the market in the future. This would have very obvious direct effects on the three scenarios and could render the results of this report obsolete (if cobalt containing LIBs were completely replaced).

15 Conclusions

This report showed that there is no immediate risk for cobalt scarcity/depletion in any of the scenarios analyzed as long as some cobalt resources will become available as reserves. The *Business as Usual* scenario (Scenario I), as expected, caused the most cobalt to be used up. Conversely, the *Technological Advancements* scenario (Scenario III) used up the least and didn't require any resources becoming reserves, indicating that the green transition is not threatened by cobalt scarcity at least when incorporating technological improvements. Scenario I, furthermore, had the largest environmental impact of all three scenarios and Scenario III had the smallest. This implies that the most important action to reduce the environmental impact of cobalt is the development of new technologies, reducing the amount of cobalt in LIBs and their market share and improving electricity mixes. For long-term sustainability of the cobalt supply chain however, higher recycling rates than those of today, like in Scenario II, are also crucial.

16 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

17 Epilogue

This report aimed to envisage what the future might look like. It did this by applying scientific study and methodology and consistently aimed to be as accurate as possible. But complete accuracy when it comes to things that have not yet happened is impossible to achieve. No matter how well researched, you can still only guess. But a guess could still provide valuable insight, a guess could help avoid problems, a guess could steer us in the right direction. We will never be able to fully predict the future, but we can prepare as best we can.

> *"Tomorrow belongs to the people who prepare for it today."*
> — **African Proverb**

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Appendix A: Processing

A.1 Flotation

Flotation of the main secondary cobalt-bearing minerals, cobalt oxides, are somewhat problematic due to their variable flotation as they are often present in primary slimes and have weak strength of the surface layer, causing high solubility and thus decreased floatability. Relatively high recovery can however be reached by flotation using either fatty acids or sulfidising the ore before flotation. The main primary cobalt mineral, cobalt sulfides, do instead have a very low solubility making them suitable for flotation in their natural state. However, these minerals are easily oxidized and thus often found with the oxidized surface, meaning surface treatment prior to flotation is critical for any efficient cobalt recovery to occur. Additionally, sulfide minerals are often charged which further complicates the flotation efficiency. Despite this, under the right conditions, primarily suitable pH, and with suitable reagents, often thiol reagents like xanthate, relatively high cobalt recovery can be reached. For example, from a carrollite mineral subjected to pH 8.5 and either xanthate, xanthic ester or a thiol blend 90 % cobalt was recovered, and from cobaltite 80 % cobalt was recovered using xanthate at pH 5 (Dehaine et al., 2021).

A.2 Leaching

The choice of leaching method depends on the quality of the extracted ore, where a higher quality ore, i.e. more rich in the desired mineral, permits the utilization of more expensive and sophisticated techniques. The two most-widely used methods, simple- and pressure leaching, each collect the ore in a vessel and let the solvent leach through the ore, but pressure leaching does this at pressures and temperatures above normal values to decrease the treatment time. Pressure leaching is performed in an autoclave. In-situ leaching is instead used when the ore is found at too low depths and quality to warrant extraction and above ground treatment. The solvent is then allowed to pass through the ore vein multiple times to dissolve the valuable mineral(s) and is subsequently pumped to the surface. For ores of a slightly higher quality (semi-low grade) heap leaching is generally used. This entails bringing the ore to the surface, putting it in heaps with collection grates or similar beneath and spraying it with solvent. The solution then collects the valuable mineral by dissolution while trickling downwards through the heap and is subsequently collected. Heap leaching is suitable for large-scale treatment of ores. The last leaching technique, tank leaching, is useful for ore deposits of higher quality and can be performed in two principal manners. Either the leach solution is circulated in very big concrete tanks along with thousands of tonnes of ore, or the ore is ground to a fine powder and low amounts are put into tanks with solvent and mixed via either aeration or mechanical perturbation. Regardless of the type of tank leaching, the pregnant solution is subsequently exposed to precipitation methods (Gill et al., 2023).

Appendix B: Refining in the Yabulu Nickel Refinery

The Yabulu Nickel Refinery in North Queensland, Australia, is a refinery that produces approximately 3.5 kt of refined cobalt per year. By looking deeper into the processes of the Yabulu refinery a more comprehensive understanding of the cobalt refining process can be gained. The Yabulu Nickel Refinery carries out both the processing and the refining stage which means it receives cobalt ore (mostly copper-cobalt and nickel-iron-cobalt ore) that is processed. The processing stage first involves pyrometallurgical processing of nickel laterite at 750 °C. This leaves reduced ore that is subsequently cooled and leached in ammonia ammonium carbonate liquor (i.e. hydrometallurgical processing). What is left is then product liquor that generally contains about 0.6 g/L of cobalt. The product liquor is then processed further resulting in a concentrated product liquor with about 1.1 g/L of cobalt. At this stage the actual refining process can commence (Fittock, 1992).

The refining stage begins by removing excess ammonia from the concentrated product liquor using a process called steam stripping. Following this, nickel is separated from cobalt via solvent extraction. The nickel is then treated in a series of processes that eventually leaves nickel metal with up to 99 % purity. The solvent extraction, simultaneously, leaves a raffinate that contains about 1 g/L of cobalt. The raffinate is first sulfided and then processed in a thickener, which allows the cobalt sulfide solids to be separated from the liquid, which then can be recycled. The solids can subsequently be oxidatively dissolved creating a cobalt sulfate solution. This solution contains plenty of impurities ranging from iron, nickel, calcium, magnesium and zinc which have to be removed. Removal is done via a four stage process involving three solvent extraction stages and one ion exchange stage. These processes leave a cobalt ammine solution with high cobalt purity, around 65 g/L. The final refining stage involves precipitating cobalt from the solution via steam stripping. The final products are thus slurry and cobalt oxide/hydroxide solids. These solids can be packaged and sold allowing for use in products (primarily batteries) (Fittock, 1992).

Appendix C: Battery Manufacturing

C.1 Cathode Active Material Production

The production of cathode active materials differs depending on both cobalt compounds used and which type of cathode is to be produced. Metallic cobalt can be heated to about 1100 K with Li_2CO_3 for 20 hours followed by reiterated grinding and heating to synthesize $LiCoO_2$ (Orman and Wiseman, 1984). Production of lithium nickel manganese cobalt oxide is conducted by mixing the transition metals, i.e. Li, Ni, Mn, Co, in the form of hydroxides, nitrates and/or sulfates (for cobalt that is then cobalt hydroxide or sulfate) with $LiOH/Li_2CO_3$ to create a precursor medium. Homogeneity of the precursor medium is achieved by either coprecipitation or milling. The medium is then calcined ("...removing volatile substances, oxidizing a portion of mass, or rendering them friable.") (The Editors of Encyclopaedia Britannica, 2021) to temperatures above 200 °C to initiate nucleation and crystal growth, followed by temperature increases to above 800 °C with enhanced crystal growth as $LiOH/Li_2CO_3$ melts and lithium + oxygen migration facilitates the formation of a NMC lattice (Wang et al., 2020). The final cobalt-containing cathode, NCA, is mostly produced via solid-state synthesis in a very similar manner to NMC. The materials, LiOH, Ni_2O_3, Co_2O_3 and $Al(OH)_3$, are mixed using e.g. mechanical milling or mortar and pestle to obtain a homogenous blend. The mixture is then pre-heated in a furnace, followed by calcination at relatively low temperatures and subsequent sintering ("the welding together of small particles of metal by applying heat below the melting point." (The Editors of Encyclopaedia Britannica, 2016) at high temperatures to achieve high strength and uniform mixing (Purwanto et al., 2018).

Appendix D: Recycling

D.1 Pretreatment

Stabilization is done with the goal of making the recycling process safer. Residual power in the battery can pose a safety risk and it is thus important to remove it in the battery which is done in three primary ways. One method is known as aqueous solution discharging which, as the name implies, uses an aqueous solution (such as NaCl, $FeSO_4$ etc.) to discharge power from the battery. Another method is known as battery conductor discharging which instead uses a conductor like copper or graphite powder. The third method is, contrarily, not based on discharging and is instead simply based on battery deactivation in an inert gas (like CO_2) (Wu et al., 2022).

Following stabilization the LIB enters the dismantling/separation stage where, simply, the LIB is dismantled and the different components are separated and the cathode materials are collected. This stage can either be performed manually or mechanically. Manual treatment uses tools such as knives, tweezers or pliers to recover materials from the LIB (cathode and anode materials, shells etc.) and is usually done in a lab. Manual treatment is not useful in industrial recycling processes but it does produce separated materials with high purity. Mechanical treatment is significantly more suitable for industry and uses comminution (reducing the LIB to smaller fragments) and separation of components. Exactly how this occurs is based on what type of components are found in the battery. Some recycling corporations go straight to this stage, skipping the stabilization and discharge process entirely. Skipping this stage results in less capital cost, less pollution and lower energy usage and is thus done in many industrial recycling processes. It does also, however, result in less lithium being recoverable (Wu et al., 2022).

The final stage of pretreatment involves separating the active electrode materials. This is an important stage as electrode materials in LIBs often are attached to current collectors, such as Cu or Al foil. Anode materials can be separated quite easily from the Cu foil as graphite and Cu foil creates weak bonds. The separation can be done via water solution treatment or more direct physical operations (for instance pulverization). As opposed to anode materials, cathode materials are difficult to separate from the Al foil as they are tightly bound to it which means simple separation is not possible. Two different ways of separating cathode materials are in use, chemical and physical. Chemical techniques range from using organic solvents to alkaline leaching of Al foil whilst physical techniques can range from mechanical crushing to ultrasonic-assisted separation (Wu et al., 2022).

D.2 Description of Several Recycling Processes In Use Today

D.2.1 Sumitomo–Sony Process

The Sumitomo-Sony process, or just Sony process, is a recycling method that resulted from the cooperation between Sony Electronics and the Sumitomo Metal Mining Company. This process has a low capacity of only 150 tonnes/year. It is, however, well adapted to recycling LIBs as it, through a pyrometallurgical process, recovers cobalt oxides that are usable in battery manufacturing (Velázquez-Martínez et al., 2019).

D.2.2 Recupyl Valibat Process

The Recupyl Valibat process, or Recupyl process, is another small scale recycling process with a capacity of about 110 tonnes/year (established in France) (Pinegar and Smith, 2019). It differs from the previous process in that it utilizes hydrometallurgy instead of pyrometallurgy. Another benefit of this process is that it is capable of recovering $LiCoO_2$ which makes it highly useful for LIBs. The process also allows for recovery of different materials, such as $Co(OH)_2$ or, if the spent LIB is processed further, elemental cobalt. This is done by first letting the LIB undergo pretreatment via a rotary shear followed by an impact mill which leaves smaller particles that are made even smaller using a vibrating screen and sieve (reaching a final size of less than 500 μm). Hydrometallurgy then follows starting with hydrolysis which allows for recovery of $LiCoO_2$ if CO_2 is added. The solid fraction that remains can be further processed, first by leaching (allowing for recovery of $(Co(OH)_2)$) and then by electrolysis which can leave elemental cobalt (Velázquez-Martínez et al., 2019).

D.2.3 Umicore Valéas™ Process

The Umicore process is a recycling process with a high capacity, about 7 000 tonnes per year in Belgium and 5000 tonnes a year in China (Pinegar and Smith, 2019). It utilizes a mixture of both pyrometallurgical and hydrometallurgical processes. First the LIB undergoes dismantling in order to remove the casing. The exposed cell is then put in a shaft furnace (i.e. the pyrometallurgical step) which results in a metallic product rich in several different metals (including cobalt). The alloy then undergoes hydrometallurgical processing which first involves leaching with a reagent and then leaching with HCl. The end product is a solution containing $Ni(OH)_2$ and $CoCl_2$. In order to get a product relevant to LIBs the $CoCl_2$ can be processed to get $LiCoO_2$ (which will be assumed as the end product of this process in this report) (Velázquez-Martínez et al., 2019).

D.2.4 Inmetco Process

The Inmetco (International Metals Reclamation Company) is a recycling process established in the United states with a capacity of about 6 000 tonnes of LIBs per year. The process is pyrometallurgical, utilizing a, after separation via milling and screening, rotary hearth furnace. The final product is an iron-cobalt-nickel alloy (Pinegar and Smith, 2019; Velázquez-Martínez et al., 2019).

D.2.5 Glencore Process

Glencore is another recycling process that mixes pyrometallurgical processing with hydrometallurgical processing. This is done by pyrometallurgically processing the LIB in a converter or rotary kiln and then putting the resultant through hydrometallurgical processing in order to obtain cobalt. The end product is consequently refined cobalt. It is established in Canada and Norway with a capacity of about 7 000 tonnes of LIBs per year (Makuza et al., 2021).

D.2.6 JX Nippon Mining and Metals Process

The JX Nippon process is a Japanese process with a capacity of about 5000 tonnes/year that combines pyrometallurgical and hydrometallurgical processes. The LIB is first incinerated in order to recover active cathode material which is then processed mechanically to get a fine material. This then undergoes leaching, solvent extraction and electrowinning which leaves refined cobalt (Botelho Junior et al., 2021; Makuza et al., 2021; Pinegar and Smith, 2019).

D.2.7 GEM High-Tech Co. Process

The GEM High-Tech Co. process is owned by one of China's and the world's biggest recycling companies (GEM High-Tech Co.). It first utilizes mechanical pretreatment in order to deactivate, separate and shred the LIB. The resulting fine material undergoes leaching (making this a hydrometallurgical process) in an acidic solution. GEM produces recycled cobalt oxides, cobalt carbonates and cobalt powder. As one of the biggest LIB recyclers the capacity of this process is very high with a cobalt oxide capacity around 25 000 tonnes/year (GEM Co., Ltd., 2021), a cobalt carbonate capacity of around 12 000 tonnes/year and a cobalt powder capacity of around 4 500 tonnes a year. GEM High-Tech also produces cathode materials usable further down the production chain (GEM Co., Ltd., 2021). It furthermore has a capacity of processing around 25 000-30 000 of LIBs per year (will be assumed to be 30 000 in this report) (Pinegar and Smith, 2019).

D.2.8 Brunp Co. Process

Brunp recycling is China's second largest recycling company and utilizes a similar hydrometallurgical process as GEM High-Tech Co., i.e. leaching pretreated spent LIBs in an acidic solution. Brunp Co. processes about 10 000 LIBs per year. Brunp Co., as GEM, also produces cathode materials as well as other cobalt products, like cobalt oxide (Brunp Co. Recycling, 2023; Pinegar and Smith, 2019).

Appendix E: Transportation

E.1 Route of Primary Cobalt

Most primary cobalt originates, as was mentioned earlier, in the DRC, specifically in the Katanga Copper Belt where the city of Kolwezi is the largest producer (Beaule, 2023). This is consequently where the first transport will take place. Cobalt will go from Kolwezi to Matadi (Figure E1) by truck with a trailer, a distance of 2325 km. Matadi being the main port city of the DRC (The Editors of Encyclopaedia Britannica, 2007b). This truck, as with all truck transports in this report, will be said to carry 60 tonnes of cargo, in this case 60 tonnes of cobalt ore.

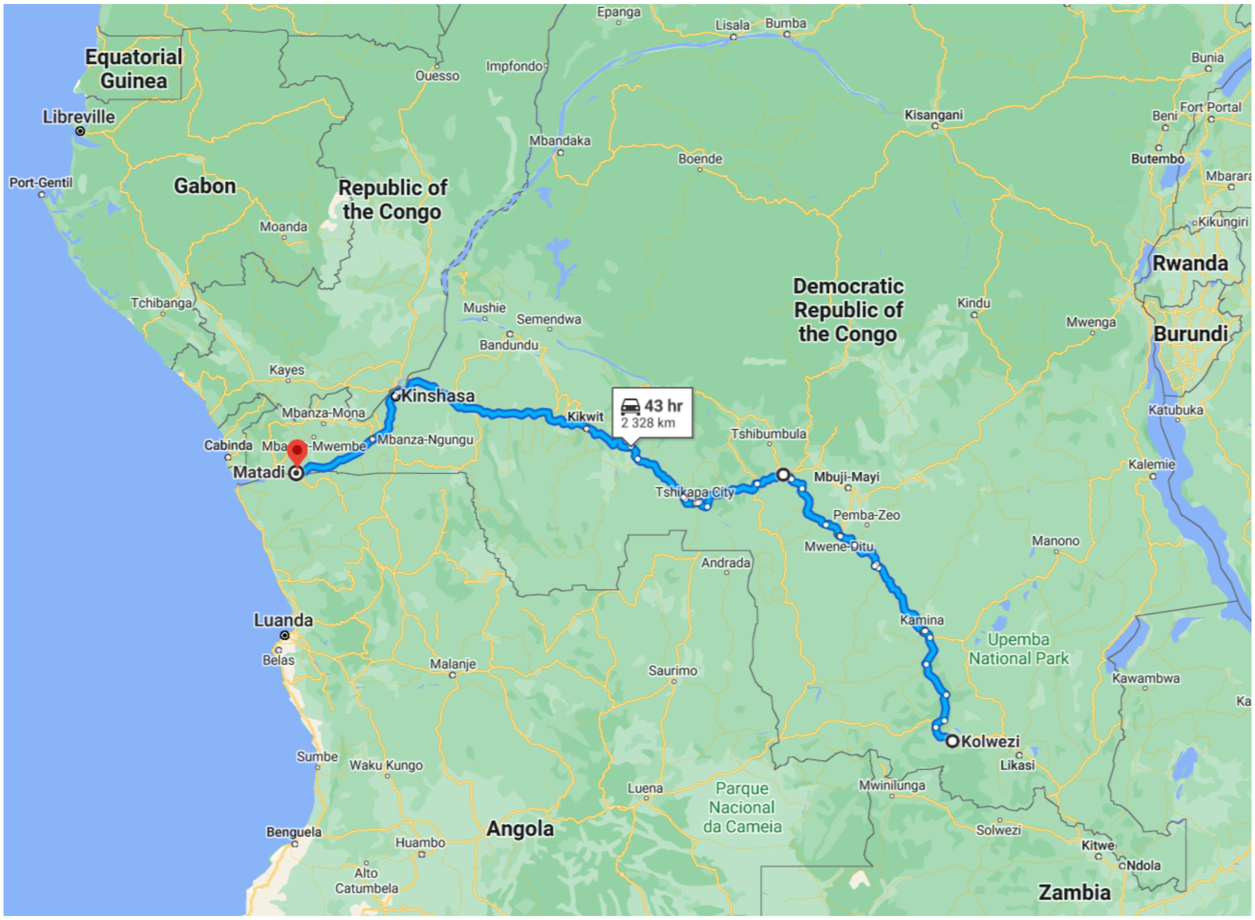

Figure E1: Route a truck takes from Kolwezi to Matadi. Distance is approximately 2330 km.

Cobalt processing and refining will, in this report, be said to take place in the same location. As the majority of both processing and refining takes place in China these stages will consequently be said to take place there as well. One of the largest cobalt refiners in China is Zhejiang Huayou Cobalt, a company based in Shanghai (Nyabiage, 2022). Huayou Cobalt operates a refinery in Quzhou, a city in the Zhejiang province south of Shanghai (WoodMackenzie, 2023). Processing and refining will be assumed to take place here. Transport from the DRC to China will be done via a bulk carrier, a large ship used to carry unpackaged cargo (in this case cobalt ore). The bulk carrier will have a deadweight tonnage of 60 000. This means that the sum of all weights on the ship, including cargo, crew, passengers, ballast, provisions etc. weighs up to 60 000 tonnes. The ship will transport the cobalt from Matadi to Shanghai (China's main port and close to Quzhou) a distance of 19 044 km. The exact route can be seen in Figure E2.

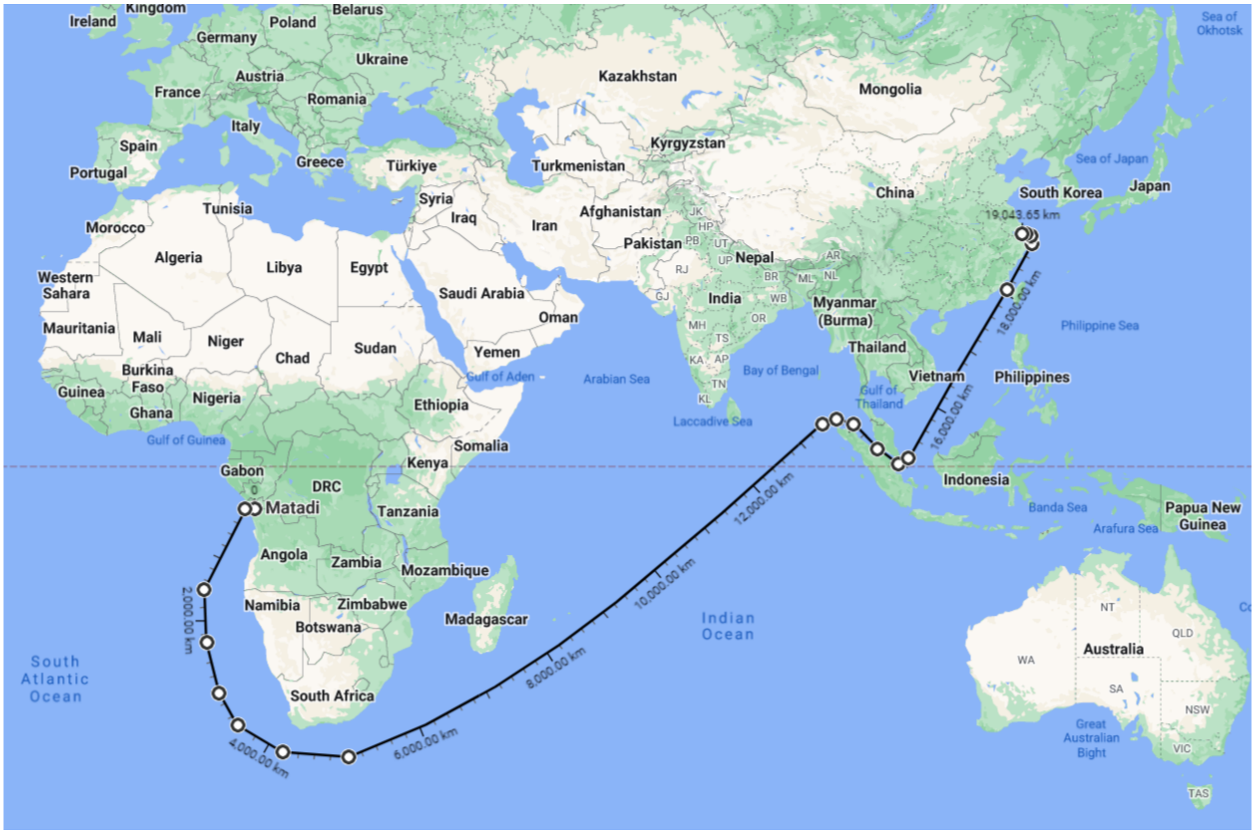

Figure E2: Route a bulk cargo ship takes from Matadi to Shanghai. Distance is approximately 19 040 km.

The cobalt must then be transported from Shanghai to the refinery in Quzhou. This is, once again, done via a 60 tonne truck with a trailer. The route distance is 405 km. Following processing and refining, the cobalt can enter the battery manufacturing stage. This is, as with previous steps, done in China. The largest LIB manufacturer in China, and the world, is CATL (KrASIA Connection, 2022). CATL is based in Ningde, Fujian province, where they also have a large production base of LIBs (Contemporary Amperex Technology Co. Limited (CATL), 2023). Battery manufacturing will thus be assumed to take place here. The route distance between Quzhou and Ningde is 410 km. See Figure E3 for the route Shanghai to Quzhou to Ningde.

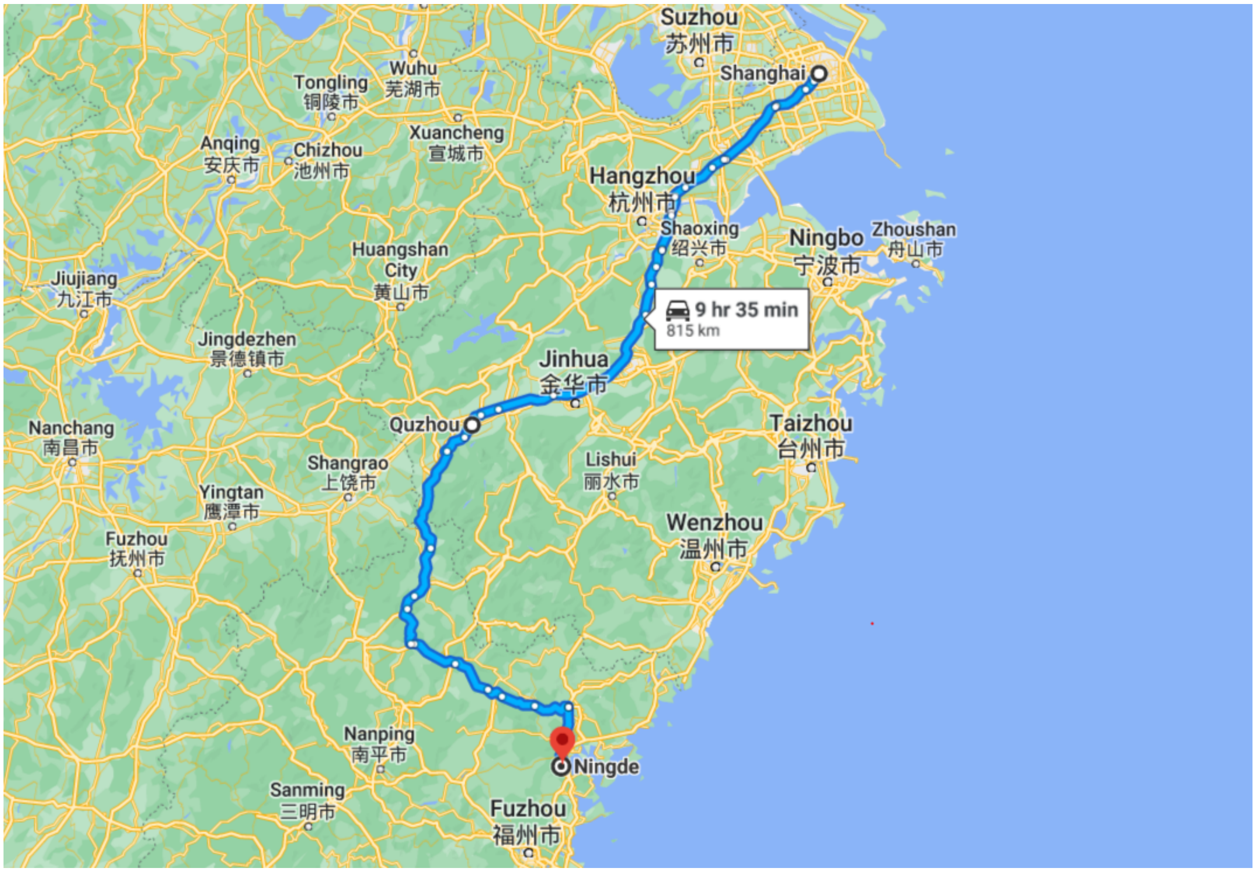

Figure E3: Route a truck takes from Shanghai to Quzhou to Ningde. Total distance is about 815 km.

Following battery manufacturing the LIB enters the use stage. Exactly what this entails in this report was described earlier. The LIB will be assumed to be directly transported to the use stage, i.e. it will be transported from Ningde to a city for sale. One of the largest markets for consumer electronics in the world is North America (Precedence Research, 2022) and as the United States is the biggest economy and the most populous country in NA the LIB will be assumed to be transported here. It will further be assumed to go to New York City as this is the most populous city in the US. This transport will be done by a 160 000 deadweight tonnage (dwt) container ship (as the LIBs are packaged cargo). A 160 000 dwt container ship will therefore transport the LIB from the port of Ningde across the pacific ocean and the Panama Canal to reach the port of New Jersey and New York (Figure E4). 9.45 % (average amount of cobalt in one LIB) of emissions from this transport will be allocated to cobalt as this transport carries LIBs, not pure cobalt. This is a distance of 20 626 km.

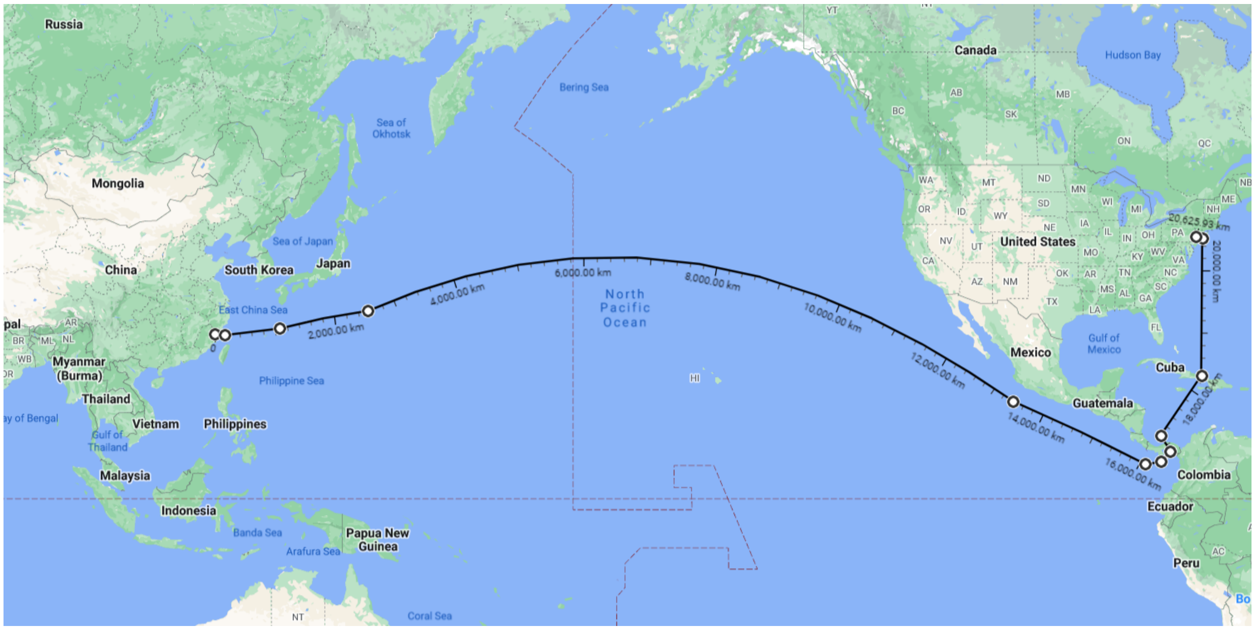

Figure E4: Route a ship takes from Ningde to New Jersey harbor. Total distance is about 20 626 km.

Finally, after the use stage, the cobalt will enter the end-of-life stage. Here the cobalt will either be transported to China for recycling (as the majority of LIB recycling occurs there) or become waste, i.e. be transported to a landfill. 37.6 % of LIBs (inverse of recycling rate) will be transported to a landfill in Albany (NYS Dept. of Environmental Conservation, 2022), a distance of 245 km (see Figure E5). Cobalt going to recycling will instead be transported via a 160 000 dwt container ship from the port of New Jersey to Shenzhen (where GEM, the largest LIB recycler, has a recycling facility (GEM, 2021)), a distance of 21 390 km (see Figure E6) (Trompiz et al., 2022). Since 2018 China has enacted much stricter regulations regarding waste imports with the National Sword policy but this does not include the banning of e-waste imports; it is thus reasonable to assume that the e-waste (LIB waste) is imported back to China (World Trade Organization, 2017a, 2017b). 9.45 % of emissions are once again allocated to cobalt.

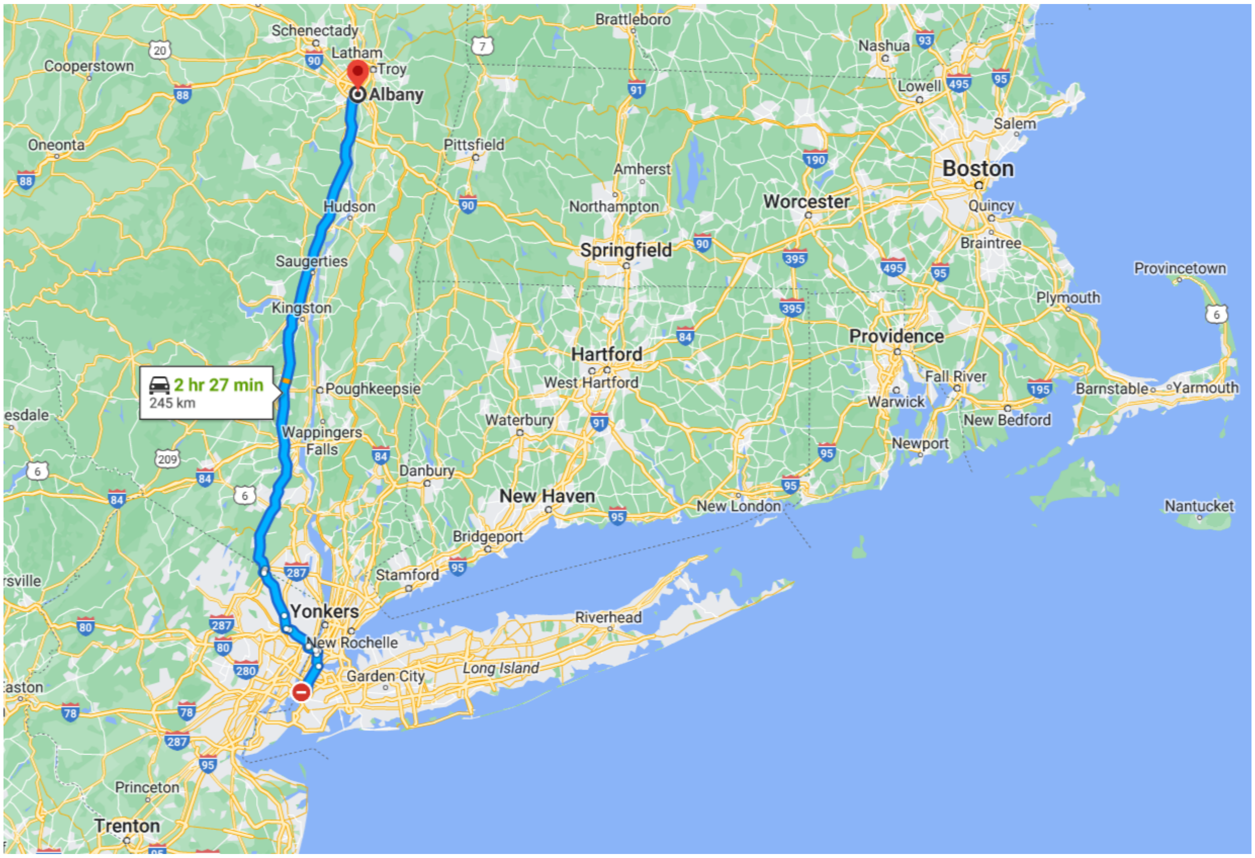

Figure E5: Route a truck takes from New York to Albany. Total distance is about 245 km.

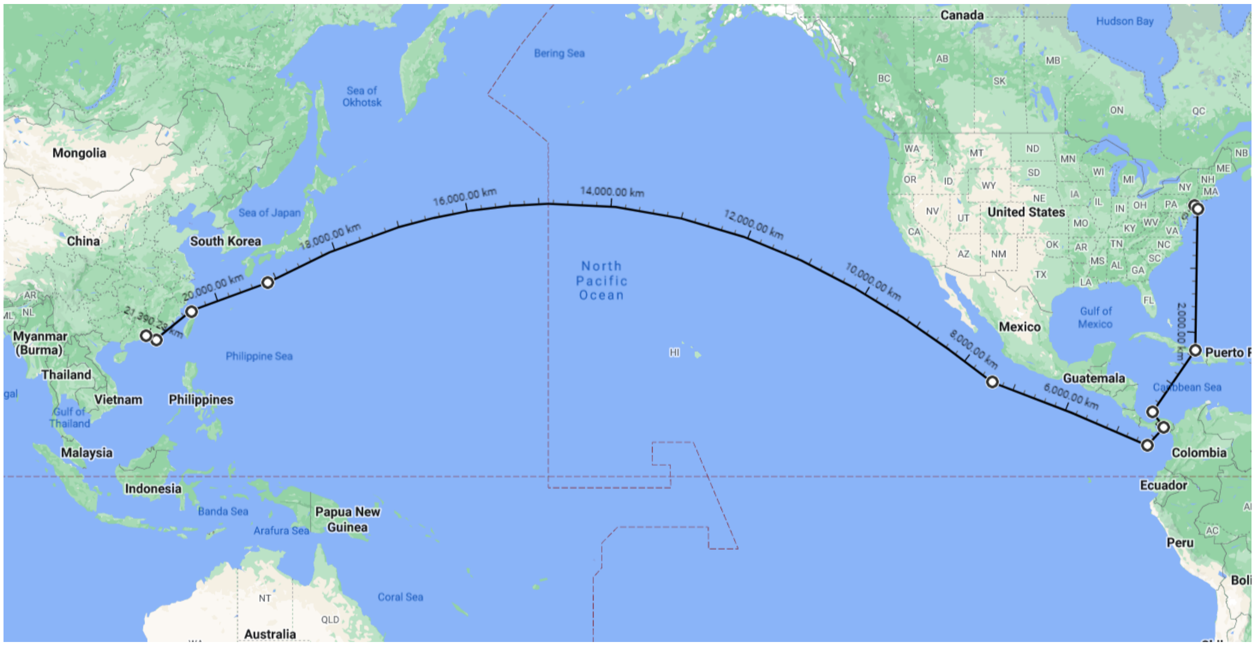

Figure E6: Route a ship takes from New York to Shenzhen. Total distance is about 21 390 km.

Assuming that all LIBs get transported distances as long as between China and the United States is, however, unreasonable, as a major consumer electronics market exists in China as well (Olorontoba, 2020; Precedence Research, 2022). Thus, half of all produced LIBs will be assumed to stay in China, meaning these LIBs will be transported a much shorter distance. These LIBs will be assumed to go to Beijing (one of the largest cities and, as it is located in the other end of the country from the refinery, a conservative assumption). The LIB will then be assumed to be transported from Beijing to Tianjin for recycling (where GEM also has a recycling plant (GEM, 2021)). Transport from Ningde to Beijing is a distance of 1812 km (Figure E7) and the transport from Beijing to Tianjin is a distance of 143 km (see Figure E8) (as LIBs are once again transported only 9.45 % of emissions go to cobalt). 37.6 % (inverse of recycling rate) will also go to a landfill which is assumed to be in Beijing (thus no transport).

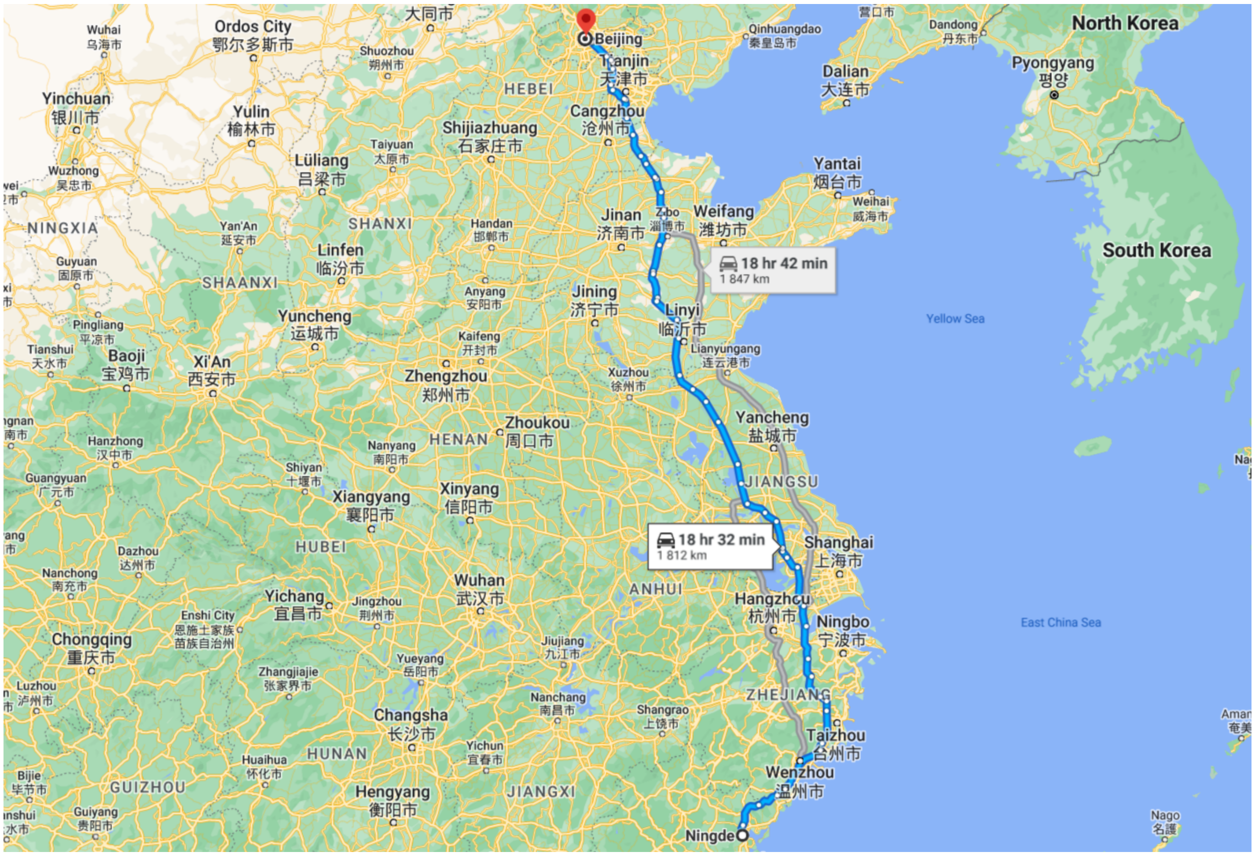

Figure E7: Route a truck takes from Ningde to Beijing. Total distance is about 1812 km.

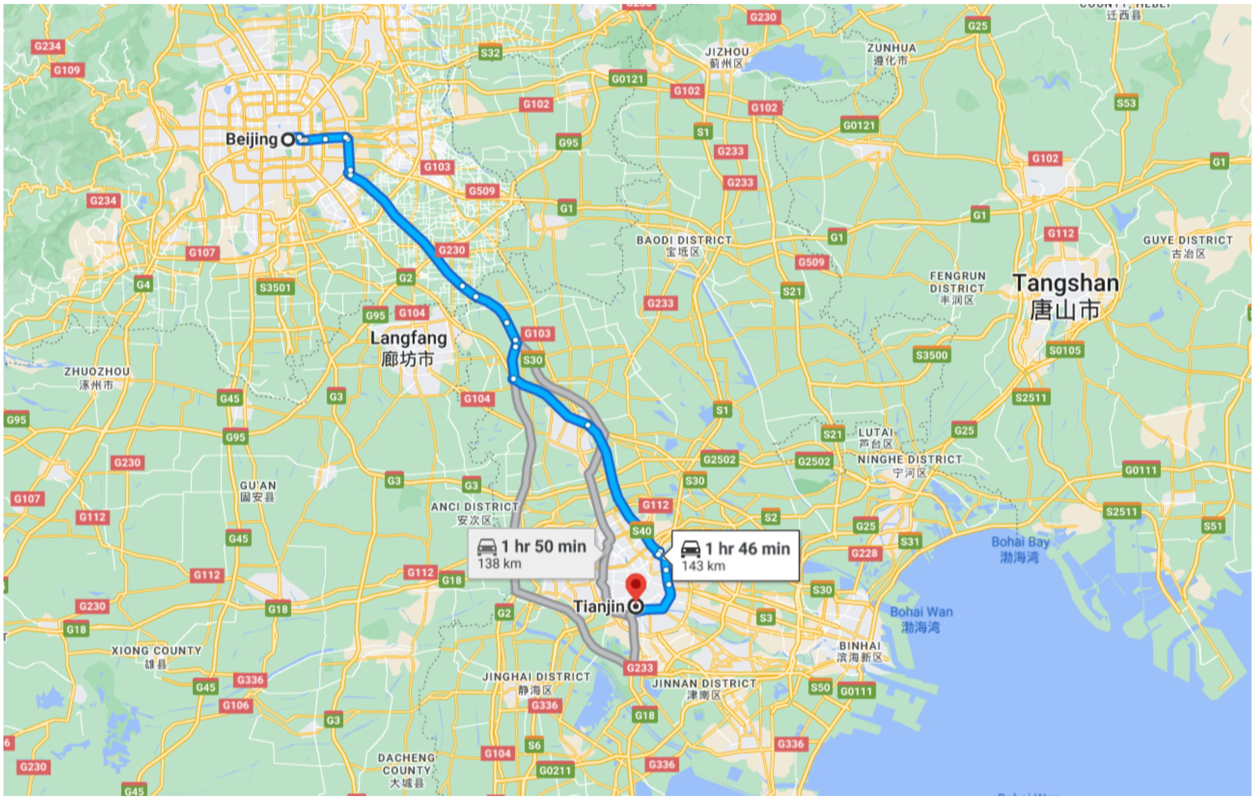

Figure E8: Route a truck takes from Beijing to Tianjin. Total distance is about 143 km.

E.2 Route of Secondary Cobalt

The transport route that was described above is, however, only applicable to primary cobalt. Secondary cobalt would not have to go through any of the early transport steps as it does not have to be extracted, processed or refined. Secondary cobalt would instead begin at the recycling facility where it would first go to battery manufacturing and then follow the same path as primary cobalt. Secondary cobalt that was used in the US will start in Shenzhen (at the recycling facility) and will first go to Ningde for battery manufacturing, a distance of 909 km (Figure E9).

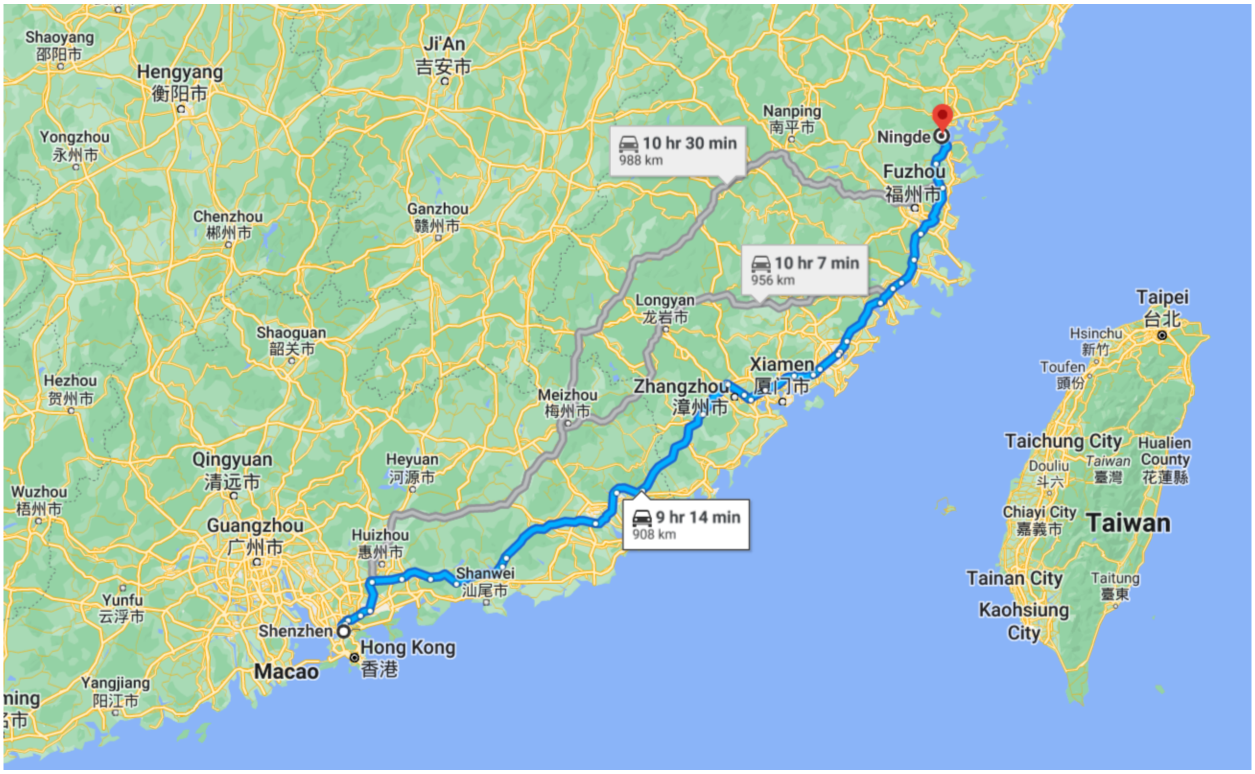

Figure E9: Route a truck takes from Shenzhen to Ningde. Total distance is about 909 km.

Secondary cobalt that was used in China will start in Tianjin (at the recycling facility) where it will first be transported to Ningde for battery manufacturing, a distance of 1672 km (see Figure E10). Following this the cobalt will go through the same transport process as primary cobalt (to Beijing and then to end-of-life).

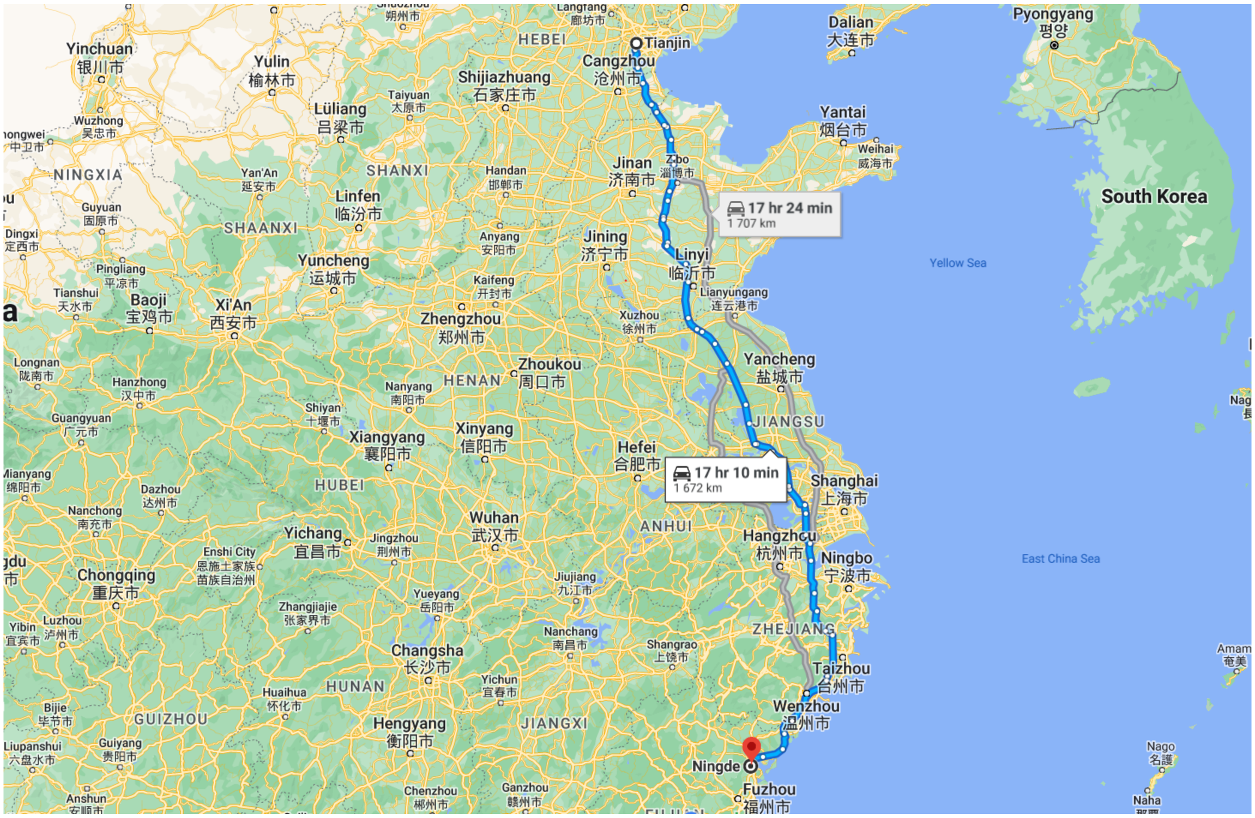

Figure E10: Route a truck takes from Tianjin to Ningde. Total distance is about 1672 km.

Appendix F: Future Mining Techniques

F.1 Deep Sea Mining

The first step to establishing a deep sea mining operation is to find suitable deposits underwater. This can be done via utilizing deep sea remote operating vehicles. These vehicles roam the seabed using cutters and drills in order to gather samples that can be brought to the surface. If a site is found that is considered to be cobalt (or any other metal) rich enough the actual operation can begin (U.S. Government Accountability Office, 2021). First, material on the seafloor that contains cobalt has to be gathered. This can be done via utilizing a vacuum dredge that sucks up large amounts of mud and materials or via drilling and cutting into the crust (U.S. Government Accountability Office, 2021). Drilling and cutting can be done with remotely controlled vehicles operating on the seafloor. The material then has to be transported above water. Two methods to do this that have been discussed since the 1960s are the continuous line bucket system and the pipe lifting system. The continuous line bucket system method uses, as the name indicates, buckets that lift minerals from the seabed to a ship moored at the surface and uses drilling and cutting to gather the materials. Combining this technique with a controller could help to make the process more efficient as the mining vehicle and the buckets could be much more coordinated. The pipe lifting system method instead utilizes, again as the name would suggest, pipes that transport the minerals to the surface and uses either pneumatic or hydraulic lifting. Pneumatic lifting goes faster than hydraulic lifting but consequently requires more energy and larger pipes (Ma et al., 2017).

F.2 Asteroid Mining

Exactly how the mining of asteroids would be performed is naturally only in the theoretical stage as of today, but the technology is not too far off. What is mainly missing at the moment is capital for some key research and testing stages. One study estimates that after 25 years has passed since the initiation of an asteroid mining program, commercial mining could be operational. The proposed way of mining asteroids by the same study was by first constructing supporting space infrastructure in the form of two space stations for refueling of rockets, manufacturing of product pods to be sent back to Earth and a system for sending the pods to Earth. The rockets, or "tugs", to be used to carry the miner and any products mined were theorized to be powered by nuclear technology but propelled using either argon or water. As water can be mined at carbonaceous asteroids this would allow the tugs to refuel propellant at the mining site saving both money and terrestrial resources. The miner complex, which was designed to consist of three miners, a processor with ore storage capacity and another nuclear power plant, would be slightly differently designed for C- and M-type asteroids but the working procedure would be similar. The whole complex lands on an asteroid, the three miners spread out to collect ores, organics, water etc., then return to the processor when miner storage is full (using water as propellant) where ores are crushed, water and organics are extracted via volatilization and valuable materials are separated and stored for transport to Earth while residues are left behind (Andrews et al., 2015). There have even been some indications that further steps of refinement of metals like leaching can be performed in-situ, further increasing the concentration of valuable metals in the payloads sent to Earth (Wouters et al., 2021).

Capital and technology are however not the only ramifications for an asteroid mining industry, since the exploitation of space is regulated by the UN treaties, the Outer Space Treaty and Moon Treaty. The Outer Space treaty, which has been ratified by most of the countries of the world (Committee on the Peaceful Uses of Outer Space, 2022), states, rather vaguely, that celestial bodies cannot be claimed by nations, companies or individuals, which could hinder asteroid mining. The Moon Treaty builds upon this and clearly states that no celestial bodies, or parts of celestial bodies or natural resources are to be owned by any state, company, organization etc. It also states that any natural resources found will be shared between all parties to the Moon Treaty with special consideration given to developing countries and the countries crucial in the finding and extraction of the resources. This is naturally not desirable for mining companies that aim for profit and could be another hindrance for future asteroid mining. As the Outer Space Treaty is somewhat vague regarding asteroid mining and since the major spacefaring nations USA, Russia and China have not ratified the Moon Treaty, some initial steps towards asteroid mining have been taken despite possible legal quandaries (Committee on the Peaceful Uses of Outer Space, 2022). These initial steps and the lack of a coverage regarding asteroids and their resources in the two treaties have caused some calls for a new treaty dealing specifically with asteroids to clarify the laws and regulations as well as avoiding lawlessness similar to that of the Californian Gold Rush (Feinman, 2013).

Appendix G: Description of Results

G.1 Extraction

The extraction of cobalt is carried out by utilizing a multitude of equipment and machines running on mainly diesel releasing emissions that have acidifying, eutrophic and/or global warming effects. The results for global warming were calculated as an even split of the effects from cobalt sulfate heptahydrate and tricobalt tetraoxide according to an LCA carried out by The Cobalt Institute (Cobalt Institute, 2021). The LCA-data was then adjusted for Scenario III by applying the electricity mix in Table 12. For acidification and eutrophication however, the values were calculated by using the diesel consumption, 0.50 kg diesel/kg Co (Dai et al., 2018), in combination with SO_2- and NO_x-emissions, in kg emissions/kg fuel (0.00015 kg SO_2/kg diesel (NETT Technologies Inc., 2020) 0.00080 kg NO_x/kg diesel (Andersson and Göransson, 2017)). The NO_x values were then converted to SO_2-eq for acidification and PO_4^{3-}-eq for eutrophication using conversion factors mentioned earlier in this study (0.7 for NO_x to SO_2-eq and 0.13 for NO_x to PO_4^{3-}-eq) (Azapagic et al., 2003). SO_2 emissions naturally required no conversion to SO_2-eq and had no eutrophic effects. In addition to this, during the extraction process approximately 7 % of the cobalt mined is lost to tailings and subsequently the environment (Whittington and Muir, 2000), causing substantial toxicological effects on both humans and aquatic ecosystems. The toxicological effects were calculated using UseTOX 2.13 (Hauschild et al., 2008; Henderson et al., 2011; Rosenbaum et al., 2011, 2008). UseTOX 2.13 did however not have any human toxicity data for cobalt so minimum risk levels from a 2023 report were used instead (Agency for Toxic Substances and Disease Registry, 2023). Minimum risk level values are lower than those normally used for toxicological calculations, which causes inflated, but still comparable, human toxicological effects of cobalt. The toxicological effects from fuel combustion were also included in the calculations using values for toxic compounds emitted from diesel (20.1 mg BaP-eq/kg diesel (Vojtisek-Lom et al., 2012)) and UseTOX.

G.2 Processing

The processing step, which includes the hydrometallurgical steps leaching and/or flotation as well as pyro- and vapometallurgy to lesser degrees, utilizes electricity and chemicals (processes as described in earlier sections) to separate cobalt from the ore. The different separation processes, mainly hydrometallurgical, cause acidifying emissions by utilizing acids as well as by electricity use. The direct SO_2-emissions from separation processes amount to 6.6 g SO_2/kg Co, which is then added together with the emissions arising from the electricity use of 1.96 kWh/kg Co, see Tables 7, 12 and Figure 1 for sulfur intensity and geographical distribution respectively. The eutrophication potential from the processing step was calculated as the AP, excluding the direct SO_2-emissions. As with the emissions from diesel use during extraction, the SO_2- and

NO_x-emissions are converted to SO_2-eq and/or PO_4^{-3}-eq using conversion factors (Azapagic et al., 2003). Other than the acidifying and eutrophic effects, the chemicals and electricity used also contributes to global warming. The GWP of the processing step was calculated by splitting the LCA data from *The Cobalt Institute* for cobalt sulfate heptahydrate and tricobalt tetraoxide evenly (Cobalt Institute, 2021) and adjusted for the changing electricity mix in Scenario III in accordance with Table 12. The toxicological data for processing was unattainable and as such only toxicological data for processing in conjunction with refining is presented.

G.3 Refining

The refining step finishes what was started during processing, by further separating and purifying the cobalt to a product that can be used in batteries. The global warming potential for the refining step was also calculated like processing and extraction using data from The Cobalt Institute (Cobalt Institute, 2021). For the *Technological Advancements* scenario, these values were adjusted for changed electricity mix according to Table 12. The data for eutrophication and acidification were instead collected from a 2022 study (Arvidsson et al., 2022) and adjusted for electricity mix like the GWP. For human and ecotoxicity, the data originates from a 2021 report (Zhang et al., 2021) and considers the impact for both the processing and refining steps due to lack of data. The HTP was converted from disability-adjusted life years to CTU_h by dividing the values with a conversion factor of 4.73 (Huijbregts et al., 2005; Zhang et al., 2021).

G.4 Product Manufacturing

The product manufacturing step, where the refined cobalt oxide and/or sulfate from the refining step is put through the steps of electrode preparation, cell assembly and electrochemistry activation with the goal of producing a functioning battery, is the most energy consuming process per functional unit and as such, rather large emissions of GHG, SO_2 and NO_x arise from the use of electricity with fossil fuels as a large portion of the electricity mix. The GWP, AP and EP were calculated in a similar manner to previous steps, where the geographical distribution of the product manufacturing step was acquired from Figure 1, electricity consumption from Table 4 and $CO_2/SO_2/NO_x$-intensity from Tables 9 and 12. Regarding allocation for the product manufacturing and for the steps that cover processes only relevant for the electrodes, 50 % of the electricity use is allocated to cobalt. Conversely, for the processes that cover the whole battery, a percentage equal to the cobalt content (9.45 % for Scenario I and II, 6.00 % for Scenario III) is allocated to cobalt. As the current product manufacturing step uses the highly toxic compound N-methylpyrrolidone as solvent, human toxicity and ecotoxicity arises from the electrode preparation step. As 99 % of the NMP used is recovered (Sliz et al., 2022) the HTP and EtP are largely inconsequential but are calculated using UseTOX.

G.5 End-of-Life

The approximate cobalt content found in one LIB is 9.45 %. To simplify calculations 1 kg of LIB cells will be assumed to contain 0.0945 kg of cobalt. Utilizing the fact that approximately 4.68

MJ are required per 1 kg of recycled cells in pyrometallurgical processes, whilst 0.125 MJ are required in hydrometallurgical processes means that pyrometallurgical recycling consumes 49.5 MJ per kg of cobalt and that hydrometallurgical recycling consumes 1.32 MJ per kg of cobalt. These values correspond to 13.8 kWh/kg cobalt for pyrometallurgical processes and 0.367 kWh/kg cobalt for hydrometallurgical processes. The next step is to divide up how much of this electricity gets, on average, consumed where, by utilizing the geographical distribution mentioned earlier, 64 % China, 24 % EU, 7 % Japan (but re-calculated to account for 100 % of production). By then taking the CO_2-eq per kWh of energy for each location, the overall global warming impact can be calculated. For pyro, in total, 6.61 kg CO_2-eq/kg cobalt. For hydro, in total 0.177 kg CO_2-eq/kg cobalt. Total, average, global warming impact can thus be calculated by utilizing how much of each recycling process is used (69.2 % hydrometallurgical and 30.8 % pyrometallurgical), 2.16 kg CO_2-eq/kg cobalt. As only about 40 % of cobalt came from recycled sources in 2050, this value is corrected to be slightly smaller, 0.860 kg CO_2-eq/kg cobalt.

The energy usage of pyrometallurgical processes and hydrometallurgical processes will still be said to be 4.68 MJ and 0.125 MJ respectively in Scenario II and III. The only difference between Scenario I and II is thus the fraction of primary vs secondary cobalt. As Scenario II has a higher fraction it has a slightly higher GWP from recycling, 1.21 CO_2-eq/kg cobalt. Scenario III, on the other hand, will, as a result of assuming less cobalt content per battery, actually have a higher energy usage per kg of cobalt than Scenario I and II. CO_2 emissions per kg of cobalt will, however, still be lower as primarily China has a far less fossil fuel intensive electricity mix in Scenario III, which means that emissions per MJ become lower. Consequently, Scenario III releases 0.102 CO_2-eq/kg cobalt.

In regards to the acidification and eutrophication potential, the calculations are the same as in the extraction step but with the energy use values from the recycling step mentioned above. Human toxicity and ecotoxicity calculations are made with UseTOX.

G.6 Transport

G.6.1 Global Warming Potential

Table G1 summarizes all emission results from the transport stage. GWP/FU is found by taking the total GWP of each transport and dividing it by the total amount of cobalt each transport carries. Trucks, as was mentioned, carry 60 tonnes of cargo, if cargo is not LIB all of this is assumed to be cobalt whilst LIBs are assumed to be 9.45 % cobalt (meaning that the truck carries 5.67 tonnes of cobalt). Bulk carriers are said to be 90 000 dwt whilst cargo ships are said to be 160 000 dwt. LIB cargo is once again said to be 9.45 % cobalt.

Table G1: Presents data for all transports. Divided between pre-use transports, transports if use stage takes place in the USA and if use stage takes place in China. Displays distance, GWP and GWP/FU. *T* denominates truck transport and *S* denominates ship transport. Sum USA shows sum of emissions if use stage takes place in USA, Sum China shows sum of emissions if use stage takes place in China.

Transport	**Distance [km]**	**GWP [CO_2-eq]**	**GWP/FU [CO_2-eq/kg cobalt]**
Pre-use			
Kolwezi-Matadi (T)	2325	10 170	0.1695
Matadi-Shanghai (S)	19 043	3 810 000	0.0635
Shanghai-Quzhou (T)	405	1 773	0.02955
Quzhou-Ningde (T)	410	1792	0.0299
Use in USA			
Ningde-New Jersey (S)	20 626	56 900 000	0.0366
New York-Albany (T)	245	1 071	0.00169
New Jersey-Shenzhen (S)	21 390	59 010 000	0.0349
Shenzhen-Ningde (T)	909	3 977	0.0663
Use in China			
Ningde-Beijing (T)	1812	5 284	0.00832
Beijing-Tianjin (T)	149	650	0.00102
Tianjin-Ningde (T)	1672	7 314	0.122
Sum USA		96 840 000	0.259
Sum China		2 315 000	0.230
Sum Total		**49 580 000**	**0.245**

G.6.2 Toxicity

The carcinogenic potential of particulate matter is measured in its benzo[a]pyrene equivalent carcinogenic potency (BaP-eq). According to a study made in 2018, heavy fuel oil (HFO) has a total BaP-eq of 0.81 mg/kg heavy fuel oil (Wu et al., 2018a, 2018b) which can, via calculations, be converted to BaP-eq per kg of cobalt. First, the amount of fuel spent per kg of cobalt in every ship transport has to be calculated. Bulk carrier transports will be said to be made by a 95 000 dwt Post Panamax bulk carrier with a typical speed of 14 knots (25.9 km/h) using 39 tonnes of fuel per day during fuel calculations whilst cargo ship transports will be said to be made by a 10 000 TEU (equivalent to approximately 36 300 tonnes (XChange, 2022)) Post Panamax cargo ship with a typical speed of 24 knots (44.4 km/h) using 240 tonnes of fuel per day (CompassAir, 2016). The results are presented in Table G2.

Similar calculations have to be made for transports made by truck. The BaP-eq value for average diesel fuel is, in this case, 1.59 mg BaP-eq/kWh according to a 2012 study (Vojtisek-Lom et al., 2012). 1 liter of diesel fuel is equivalent to approximately 9.96 kWh (Statistiska Centralbyrån, 2009) which means that the BaP-eq value is equivalent to 15.8 mg BaP-eq/l of diesel fuel. All transport is assumed to be done by the same type of truck, a 60 tonne truck with a trailer using 0.492 l of fuel per km. Thus the amount of liters each journey requires per kg of cobalt is calculated in order to get total CTU_e/kg cobalt and CTU_h/kg cobalt.

Table G2: Fuel usage in each individual transport step as well as fuel use per functional unit.

Transport	**Diesel Fuel [l]**	**Heavy Fuel Oil [kg]**	**Diesel Fuel/FU [l/kg cobalt]**	**Heavy Fuel Oil [kg/kg cobalt]**
Pre-use				
Kolwezi-Matadi (T)	1144		0.0191	
Matadi-Shanghai (S)		1195000		0.0126
Shanghai-Quzhou (T)	199		0.00332	
Quzhou-Ningde (T)	202		0.00336	
Use in USA				
Ningde-New Jersey (S)		4645000		0.0121
New York-Albany (T)	245		0.000190	

New Jersey-Shenzhen (S)		4818000		0.0125
Shenzhen-Ningde (T)	909		0.00745	
Use in China				
Ningde-Beijing (T)	1812		0.00140	
Beijing-Tianjin (T)	149		0.000115	
Tianjin-Ningde (T)	1672		0.0137	

With fuel calculations done, the toxicity of each transport step can be calculated. First the carcinogenic potential in BaP-eq/FU is calculated using the value mentioned earlier. The BaP-eq can then be converted to CTU_e and CTU_h (aquatic ecotoxicity and human toxicity) by using UseTOX. The results are presented in Table G3.

Table G3: Carcinogenic potential in BaP-eq/FU, aquatic ecotoxicity potential in CTU_e/FU and human toxicity potential in CTU_h/FU for each individual transport step.

Transport	**Carcinogenic Potential [kg BaP-eq/kg cobalt]**	**Aquatic Ecotoxicity Potential [CTU_e/kg cobalt]**	**Human Toxicity Potential [CTU_h/kg cobalt]**
Pre-use			
Kolwezi-Matadi (T)	3.02E-07	1.70E-05	7.91E-10
Matadi-Shanghai (S)	1.02E-08	2.41E-09	8.66E-12
Shanghai-Quzhou (T)	5.26E-08	2.97E-06	1.38E-10
Quzhou-Ningde (T)	5.32E-08	3.00E-06	1.39E-10
Use in USA			
Ningde-New Jersey	9.80E-09	2.32E-09	8.33E-12

(S)			
New York-Albany (T)	3.01E-09	1.70E-07	7.88E-12
New Jersey-Shenzhen (S)	1.02E-08	2.41E-09	8.63E-12
Shenzhen-Ningde (T)	1.18E-07	6.66E-06	3.09E-10
Use in China			
Ningde-Beijing (T)	2.22E-08	1.25E-06	5.83E-11
Beijing-Tianjin (T)	1.83E-09	1.03E-07	4.79E-12
Tianjin-Ningde (T)	2.17E-07	1.22E-05	5.69E-10
Sum	**3.35E-07**	**1.81E-05**	**8.52E-10**

Total emissions from all transports become 1.81E-5 kg CTU_e/kg cobalt and 8.52E-10 kg CTU_h/kg cobalt.

G.6.3 Acidification

Acidification is estimated using SO_2 emissions. Thus total acidification is given in SO_2-eq which can be calculated by estimating both pure SO_2-emissions and NO_x-emissions. Approximately 28.63 g SO_2/kg fuel is emitted during HFO combustion (Wu et al., 2018b) which is used for pure SO_2 emissions. The NO_x emissions multiplied by 0.7 (Azapagic et al., 2003) can then be added to these values to get total emissions from all ship transports. Truck emissions are calculated in the same manner. SO_2 emissions from truck transports are approximately 0.000128 kg SO_2/l fuel (NETT Technologies Inc., 2020). The AP for every transport step can be seen in Table G4.

Table G4: Acidification potential in kg SO_2-eq/FU for each individual transport step.

Transport	**Acidification [kg SO_2-eq/kg cobalt]**
Pre-use	
Kolwezi-Matadi (T)	2.05E-05
Matadi-Shanghai (S)	8.31E-04
Shanghai-Quzhou (T)	3.56E-06
Quzhou-Ningde (T)	3.61E-06

Use in USA	
Ningde-New Jersey (S)	7.99E-04
New York-Albany (T)	2.04E-07
New Jersey-Shenzhen (S)	8.29E-04
Shenzhen-Ningde (T)	8.00E-06
Use in China	
Ningde-Beijing (T)	1.51E-06
Beijing-Tianjin (T)	1.24E-07
Tianjin-Ningde (T)	1.47E-05
Sum	**1.19E-03**

Total emissions become 1.19E-3 kg SO_2/kg cobalt.

G.6.4 Eutrophication

According to the same report that found BaP-eq values from HFO emissions, combustion of HFO releases approximately 51.6 g NO/kg fuel and 1.93 g NO_2/kg fuel, i.e. 53.5 g NO_x/kg fuel (Wu et al., 2018b). Using the same calculations as when calculating toxicity, emissions for each shipping transport can be calculated. Approximately 0.00135 kg NO_x/l fuel is emitted during truck transports (Andersson and Göransson, 2017). With this, emissions from truck transports can also be calculated using the same type of truck as in the acidification calculations. Eutrophication potential is given in kg PO_4^{3-}/FU which means NO_x values have to be converted. This is simply done by multiplying each NO_x value with 0.13 (Azapagic et al., 2003). Results are presented in Table G5 below.

Table G5: kg NO_x/FU and eutrophication potential in kg PO_4^{3-}-eq/FU for each individual transport step.

Transport	**[kg NO_x/kg cobalt]**	**Eutrophication Potential [kg PO_4^{3-}-eq/kg cobalt]**
Pre-use		
Kolwezi-Matadi (T)	2.57E-05	3.35E-06

Matadi-Shanghai (S)	6.73E-04	8.75E-05
Shanghai-Quzhou (T)	4.48E-06	5.83E-07
Quzhou-Ningde (T)	4.54E-06	5.90E-07
Use in USA		
Ningde-New Jersey (S)	6.47E-04	8.41E-05
New York-Albany (T)	2.56E-07	3.33E-08
New Jersey-Shenzhen (S)	6.71E-04	8.72E-05
Shenzhen-Ningde (T)	1.01E-05	1.31E-06
Use in China		
Ningde-Beijing (T)	1.90E-06	2.46E-07
Beijing-Tianjin (T)	1.56E-07	2.03E-08
Tianjin-Ningde (T)	1.85E-05	2.41E-06
Sum	**9.71E-04**	**1.26E-04**

Total emissions become 1.26E-04 kg PO_4^{3-}/kg cobalt.

G.6.5 Scenario II and Scenario III

The only difference between Scenario I and Scenario II when it comes to transport is the recycling rate, 90.25 % in 2050 (which results in 58 % of cobalt coming from secondary sources in 2050). The calculations are thus the exact same with the only difference being that more cobalt goes to recycling. Several variables change when calculating transport in Scenario III. The first is cobalt content which is reduced from 9.45 % to 6.00 % which in turn reduces the environmental impact of all categories. The primary supply fraction is, on the other hand, higher in Scenario III than Scenario I which means a higher percentage of cobalt comes from mining than recycling in this scenario. Truck fuel usage will also be reduced by 50 %, from 0.492 l/km to 0.246 l/km based on data that was discussed in the technological advancement section. Ship fuel usage will be said to follow the 1.5 °C scenario and will thus be reduced by 44 %. Post Panamax bulk carrier fuel usage is consequently reduced to 21.8 MT/day whilst Post Panamax cargo ship fuel usage is reduced to 134 MT/day.