

Maria Bollwein

# Comparative life cycle assessment of prospective battery-grade material production in Norway

## Modeling the value chains of nickel-, cobalt-, and manganese Sulfate

Master's thesis in Sustainable Energy

Supervisor: Anders Hammer Strømman

Co-supervisor: Nelson Bunyui Manjong and Lorenzo Usai

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# Abstract

The manufacturing of battery grade materials is electricity intensive and currently dominated by China. Several European countries are exploring options of venturing into locally produced raw materials for battery manufacturing. In Norway, four battery manufacturing facilities are planned or under construction which increases the need for locally manufactured battery grade materials. This study investigates the potential impacts of producing nickel, cobalt and manganese sulfate in Norway, a country known for its renewable-sourced electricity. A high resolution model is developed for each of the three battery grade materials which considers individual steps of the value chain from mining to the final product. This is vital in the modelling as some processes, especially those pertaining to mining and ore processing occur outside of Norway. Environmental impacts of these battery grade materials are performed with Arda, an in house LCA calculator using ReCiPe2016 as midpoint characterization method.

The results show that, producing nickel and cobalt sulfate in Norway yields 3.3kg  $CO_2eq.$  and 7.7kg  $CO_2eq.$ , respectively, with the highest contribution from ore processing which occurs in Canada. Manganese sulfate produced in Norway with ores mined in Gabon causes a GWP of 1.3kg  $CO_2eq.$ , mainly due to metal refining impacts. The results are benchmarked with other studies performed across different geographical system boundaries to depict the emission reduction opportunities in producing these battery grade materials in Norway. What is observed is that, production of these sulfates in Norway has significant emission reduction benefits as compared to other studies reported in the scientific literature. To increase the robustness of the analysis, the thesis further develops scenarios to investigate the effect of changes in the electricity mix intensity of different mining and production countries on the overall GWP. Within these scenarios, the Norwegian case still emerges with the lowest GWP. Results of this study indicate that producing battery grade materials in Norway has prospects of reducing the emissions associated with cell materials in lithium-ion batteries. Furthermore, from the scenarios developed, the GWP of cathode precursors can be significantly reduced by using low carbon electricity in both mining and producing countries.

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Maria Bollwein, Trondheim, Spring 2022

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# Nomenclature

## Case-specific terminology

|                                  |   |
|----------------------------------|---|
| <i>Battery-grade material</i>    | Nickel-, cobalt-, and manganese sulfate are battery-grade materials used in battery cathodes.   |
| <i>Metal refining</i>            | The processing and refining of intermediate materials to metals through various production routes. Metal refining takes place in the producing country. |
| <i>Mining and ore processing</i> | Sub-processes are ore mining, beneficiation, and primary extraction grouped as all happen in the mining country to provide intermediate materials.      |
| <i>Mining country</i>            | Mining and ore processing takes places in countries that typically bear ore deposits.   |
| <i>Producing country</i>         | Metal refining and sulfate production takes place in countries that are typically industrialized countries.   |
| <i>Sulfate production</i>        | The chemical process of synthesising a metal to form a metal sulfate. Sulfate production takes place in the producing country.                          |

## Impact categories

|             |                              |
|-------------|------------------------------|
| <i>ALOP</i> | Agricultural land occupation |
| <i>FDP</i>  | Fossil depletion             |
| <i>FEP</i>  | Freshwater eutrophication    |
| <i>FETP</i> | Freshwater ecotoxicity       |
| <i>GWP</i>  | Global Warming Potential     |
| <i>HTP</i>  | Human toxicity               |
| <i>IRP</i>  | Ionizing radiation           |

|                        |  |
|------------------------|--|
| <i>MDP</i>             | Metal depletion                              |
| <i>MEP</i>             | Marine eutrophication                        |
| <i>METP</i>            | Marine ecotoxicity                           |
| <i>NLTP</i>            | Natural land transformation                  |
| <i>ODP</i>             | Ozone depletion                              |
| <i>PMFP</i>            | Particulate matter formation                 |
| <i>TAP</i>             | Terrestrial acidification                    |
| <i>TETP</i>            | Terrestrial ecotoxicity                      |
| <i>ULOP</i>            | Urban land occupation                        |
| <i>WDP</i>             | Water depletion                              |
| <b>Methodology</b>     |  |
| <i>D<sub>pro</sub></i> | Impacts per process per external demand      |
| <i>AF</i>              | Allocation factor                            |
| <i>A</i>               | Requirement matrix                           |
| <i>C</i>               | Characterization matrix                      |
| <i>d</i>               | Impacts per external demand                  |
| <i>E</i>               | Stressors related to external demand, matrix |
| <i>e</i>               | Stressors related to external demand, vector |
| <i>FU</i>              | Functional unit                              |
| <i>imp</i>             | Impact category                              |
| <i>LCA</i>             | Life cycle analysis                          |
| <i>L</i>               | Leontief inverse                             |



|            |                                  |
|------------|----------------------------------|
| <i>pro</i> | Process                          |
| <i>SPA</i> | Structural path analysis         |
| <i>str</i> | Stressor                         |
| <i>S</i>   | Stressor matrix                  |
| <i>x</i>   | Total output                     |
| <i>y</i>   | External demand, functional unit |

### **Materials**

|                         |                   |
|-------------------------|-------------------|
| <i>CoSO<sub>4</sub></i> | Cobalt sulfate    |
| <i>MnO<sub>2</sub></i>  | Manganese oxide   |
| <i>MnSO<sub>4</sub></i> | Manganese sulfate |
| <i>NiSO<sub>4</sub></i> | Nickel sulfate    |
| <i>Co</i>               | Cobalt            |
| <i>Mn</i>               | Manganese         |
| <i>Ni</i>               | Nickel            |
| <i>FeMn</i>             | Ferromanganese    |

### **Other symbols**

|             |   |
|-------------|---|
| <i>BEV</i>  | Battery electric vehicle                  |
| <i>DRC</i>  | Democratic republic of the Congo          |
| <i>EU</i>   | European Union                            |
| <i>ICE</i>  | Internal combustion engine                |
| <i>IPCC</i> | Intergovernmental Panel on Climate Change |
| <i>NMC</i>  | Nickel manganese cobalt cathode material  |
| <i>UNEP</i> | United Nations Environmental Programme    |
| <i>USGS</i> | United States geological survey           |

# 1 Introduction

## 1.1 Background

In recent years consequences and urgency of climate change were revealed to be one of the biggest threats to humanity (Reser and Swim, 2011). Goal 13 of the United Nation's Sustainable Development Goals calls for immediate action to enforce stronger climate policies and to reduce emissions (United Nations, 2021). To lower the risks and impacts of global warming in the future, the Paris Agreement from 2016 has become one of the most acknowledged climate policies and was adopted by 196 nations. It concludes that a fundamental reduction of carbon emissions in the near future is required to remain below the 1.5 °C target by 2050 (United Nations. Framework Convention on Climate Change, 2015).

Initiated by the United Nations Environment Programme (UNEP), the Intergovernmental Panel on Climate Change (IPCC) reports have established a governing source for wide-ranging scientific assessment on anthropogenic climate change. Technical summaries and incentives for policymaking identify the main drivers, propose pathways and specify required climate action for high-emission sectors (United Nations Environmental Programme (UNEP), 2022). In 2010, the transportation sector produced 23% of the energy-related carbon emissions and was predicted to be the strongest growing sector in the 2014 IPCC report. One of the crucial mitigation options in road transportation is to replace conventional internal combustion engine vehicles (ICE) with battery-electric vehicles (BEV) (Sims et al., 2014). In 2021, only seven years later, 3.3 million battery-electric vehicles were sold in China, 2.3 million in Europe, and 0.6 million in the United States. The BEV market keeps growing, and the impact from the transportation sector started to decrease as a consequence. Yet, further emission reductions are required to reach climate targets (International Energy Agency, 2022).

Tailpipe emissions for BEVs have been minimized successfully, but the carbon emissions from producing a vehicle battery can make up to 80% of the lifelong emissions of an ICE vehicle (Nickischer, 2020). Lithium-ion batteries are the preferred choice for BEVs and the material composition within the battery is crucial. Particularly the share of nickel-, cobalt-, and manganese sulfate in the

cathode determines the performance of a battery (Dai et al., 2019). 15% of the total battery emissions are allocated to the production of the cathode (Dunn, Gaines, et al., 2015). Mining and ore processing, metallurgical refining and the synthesis to the metal sulfate are required to form the respective sulfate. These processes bear high carbon emissions because of high energy- and electricity demands (Dunn, James, et al., 2015). To reduce the emissions of battery production, the impacts of producing nickel-, cobalt and manganese sulfate need to be reduced.

## **1.2 Production of Battery-Grade Materials**

China is today's monopolist in the battery manufacturing and holds furthermore 70% of the world's cathode production (International Energy Agency, 2022) (Dunn, James, et al., 2015). The country's electricity mix is dominated by burning fossil fuels and due to the high electricity demand in the battery and cathode production, the carbon emissions of Chinese production are immense. Consequently, the production processes bear high emission reduction potential by shifting towards the use of low-carbon electricity mix (International Energy Agency, 2020). Europe as the world's second largest market for BEVs, has started to realize the urgency of climate change. By 2030, the European Union (EU) aims to bring light duty vehicle emissions down to 45% relative to 1990 levels (European Commission, 2020a)(International Energy Agency, 2022). In 2020, the European Commission revised regulations in the battery directive and proposed incentives for a 'sustainable battery' in the European Green Deal (European Commission, 2020a). Accordingly, the environmental impact and carbon emissions of batteries that are produced and used within the EU should be brought to a minimum throughout the entire life cycle. Thus, not only the production of the battery, but also the production of battery-grade materials requires low-emission value chains (European Commission, 2020b). Shafique and Luo, 2022 analysed the impact of electricity mixes on the production of BEVs and concluded that production in China causes the highest, while future production in Norway yields the lowest environmental impact and carbon emissions as the country strongly relies on renewable energy sources (International Energy Agency, 2020). Combined with the incentives of the European Green Deal, Norway is a one of the most favorable countries to produce batteries within the EU as it fulfills requirements for low-carbon production of battery-grade materials.

Along with the growing battery industry, the attention of research towards the environmental impact of batteries has increased enormously in recent years. The environmental impacts of the battery assembly as part of the BEV life cycle have been well investigated in form of life cycle analysis (LCA). A LCA analyses the cumulative impact of a material or product throughout the different stages of its life cycle and quantifies the resulting impact for different environmental impact categories (International Organization for Standardization, 2006) (Strømman, 2010).

Despite the high energy- and electricity intensity of the cathode production, only few research has been conducted on the environmental impacts of the above-mentioned cathode materials nickel-, cobalt-, and manganese sulfate and the overall data availability is found out to be limited. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) has identified this research gap and is to this date the sole provider of a complete set of environmental impacts for producing nickel-, cobalt- and manganese sulfate (Dai et al., 2019). What makes the GREET model valuable is that the impacts are provided for each of the three materials in coherent value chains. Thus, impacts can be compared quantitatively since systematic errors are eliminated and the methodological approach is identical. With these values, the GREET model provided fundamental data for several LCAs on the potential reduction impact of BEV batteries, amongst which is the often-cited study by Romare and Dahllöf, 2017. Sufficient in the context of analysing overall impacts of a battery as for Romare and Dahllöf, 2017, a major limitation of the GREET model is that the impacts of each material are reported in a one score only which hinders the identification of high-impact processes along the value chain. This restriction applies to all publicly available LCA data on battery-grade materials. The only exception is the Nickel Institute, which provides process-oriented impacts for the production of nickel sulfate and indicates significant impacts from ore processing and refining on climate change (GWP) (Gediga and Boonzaier, 2021). For producing cobalt sulfate, Chordia, Nordelöf, and Ellingsen, 2021 suggest slightly higher GWP impacts for Canada, than the globally averaged GREET model, while Rinne, Elomaa, and Lundström, 2021 for Finland, and T. Zhang et al., 2021 for China report impacts that are more than five times higher.

These are the only publicly available studies that conduct a LCA for the full value chain of producing nickel-, cobalt-, and manganese sulfate. Due to the low data

availability and largely varying impacts, further investigation is needed. To get a better understanding on the impacts of battery-grade materials, individual value chains can be modeled in process-oriented sections, since typically the sulfate production as the last process is missing. Impacts from value chains that begin with mining and end after the metal refining process, are reported in several LCAs. To produce nickel class I, Gediga and Boonzaier, 2021 from the Nickel Institute provide detailed data and process-based impacts for the global average. Slightly higher impacts than these by the Nickel Institute are proposed by Wei et al., 2020 and Norgate, Jahanshahi, and Rankin, 2007 who both assess the nickel production in Australia under aspects of different allocation methods and varying production processes. Similarly, Bai et al., 2022 and Deng and Gong, 2018 analyse the impacts of nickel production for different production processes in China. Impacts for cobalt production were found to be available for the global average, only. Meide et al., 2022 focuses on the impact of varying allocation methods and reports relatively low GWP impacts for cobalt production. Significantly higher are the results by Farjana, Huda, and Mahmud, 2019, whose study is developed from ecoinvent database processes. Much higher GWP impacts are reported by the Cobalt Institute, 2020 without further available details. Since no full value chain for manganese sulfate could be found, alternative value chains are highly relevant, but also found to be scarce. Westfall et al., 2016 provides the impacts of producing ferromanganese under the global average, and R. Zhang et al., 2020 calculates the impacts of producing electrolytic manganese. Even without the sulfate production process included, both studies yield up to four times higher than the GREET model and opens questions on whether or not the resulting impacts are mutually exclusive.

In conclusion, data availability is low for both full value chains and partial sections of the production of nickel-, cobalt-, and manganese sulfate. Reported values for the metal production are highest for cobalt and nickel but since all values are provided as a single score, the origin of impacts cannot be clearly identified. Aligned with the conclusion by Shafique and Luo, 2022 mentioned in the previous section, the production in China compared to other countries, appears to have the highest impact from producing battery-grade materials.

### **1.3 Aim and Objective**

Under the scope of decarbonising the transportation sector, battery-electric vehicles as a low-carbon alternative to conventional vehicles have been established in recent years, and the market keeps growing. However, batteries bear trade-offs and the production, especially the production of battery-grade material for cathodes, requires high amounts of energy and electricity. Following the EU's incentives of producing 'sustainable batteries' in Europe, Norway qualifies as the country with the highest use of renewables (International Energy Agency, 2020). Thus, the following research questions are defined:

1. What is the environmental impact of battery-grade materials that are refined and produced in Norway?
2. How can regionally varying electricity mixes affect the global warming potential for producing battery-grade materials?

Under the scope of this study, several LCAs were conducted, analysed, and benchmarked. To answer the first research question, three LCAs were conducted to assess the impact of producing nickel-, cobalt- and manganese sulfate in Norway. The second research question focuses on the impact of varying regional electricity mixes. Thus, three scenarios with distinct mining- and producing countries were modeled and assessed through LCA for each of the three materials.

### **1.4 Structure of the Thesis**

Understanding the governing LCA methodology and how it relates to the topic is crucial for obtaining high-quality results. This is complementary explained in Chapter 2 and Chapter 3, which describe the LCA framework and the case of this study. Chapter 3 holds the case description and explains the fundamental elements of an LCA, i.e., goal and scope, inventory modeling and impact assessment in the context of the research questions. The inventory modeling for the production of nickel-, cobalt- and manganese is a major contribution of this thesis. Establishing complete, detailed, and coherent value chains with mostly industry-based data is

novel to the field of battery-grade materials and allows process-oriented impact assessment of the obtained LCA results.

The resulting impacts for battery-grade material production in Norway answer the first research question and are presented and analysed in Chapter 4. First, environmental impacts for all available impact categories are presented for each of the three materials. Secondly, the GWP impact is further analyzed and benchmarked to literature-based value chains. Chapter 4 provides also results the impact of varying regional electricity mixes on the GWP of each material under the scope of the second research question.

In Chapter 5, key findings are discussed under the aspects of parameters that were identified to bear strong GWP impact reduction potential in the mining and producing of nickel-, cobalt- and manganese sulfate. Furthermore, this chapter includes limitations and recommendations for future work. The most relevant findings of this study are concluded and incentives for the battery industry are proposed.

Chapter 6 summarizes and concludes the main findings of this work.

Under the scope of this thesis, detailed and process-oriented inventories for the main process steps in the production of nickel-, cobalt- and manganese sulfate were established and are presented in Appendix A.

Appendix B provides LCA results for all impact categories and process steps, for each of the three battery-grade materials that were discussed in 4. This study focuses on the impacts on GWP, but terrestrial acidification (TAP) and particulate matter formation potential (PMFP) are other highly relevant impact categories in the context of battery production.

Available literature data for TAP and PMFP impacts was not sufficient for a reliable discussion in the scope of this thesis. TAP and PMFP impacts were estimated for Norwegian production and benchmarked to literature. Results are further attached in Appendix B to provide foundation for future research.

## 2 Methodology

The first form of life cycle assessment (LCA) dates back to the early 1970s and represents the effort of comparing the energy use of two different products. In the following decades, the relevance and interest in LCA started to grow. Further life cycle stages began to be included, and first methodologies for impact assessments were established (Guinee et al., 2011). Today, LCA proposes quantified, transparent and informative environmental assessment data, which is crucial in numerous fields like policy making, identifying impact reduction potential, product declaration, etc. Diversity and application range of LCAs kept increasing and required a standardized process to ensure understanding, impartiality, and correctness (International Organization for Standardization, 2006).

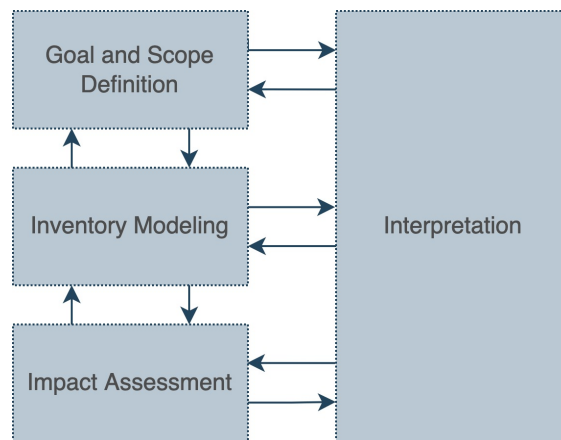


Figure 2.1: The four stages of life cycle analysis according to the LCA framework by International Organization for Standardization, 2006.

The international standard ISO14044, a directive for life cycle assessment was established by the International Organization for Standardization, 2006. The standard concludes that LCA is used to quantify existing or potential environmental impacts of products or services throughout parts of their life span, or the full life cycle from raw material until disposal or recycling. The characteristic



methodology of LCAs is now given through the LCA framework as shown in Figure 2.1. The four main stages of LCA are 1) defining a precise goal and scope, 2) developing a life cycle inventory, and 3) conducting impact assessment. Stage 4) represents constant interpretation within the individual stages to ensure coherence (International Organization for Standardization, 2006).

## 2.1 Goal and Scope

The goal and scope of an LCA present the reasons for conducting the study, clarify the exact purpose, and define to whom the LCA results are addressed to. Based on these considerations, the functional unit (FU) of the study is selected (Strømman, 2010). The functional unit is usually the product or material of interest. To understand and compare the LCA results later on, the FU must be comprehensive, clearly quantified, an example of a FU could be 1kg cobalt sulfate. Further defined in the goal and scope stage is the system boundary, i.e., which stages of life cycles are included in the assessment (International Organization for Standardization, 2006). A common system boundary is ‘cradle to gate’ which considers the impacts from raw materials to the finished product (Strømman, 2010). In the case of the above-mentioned example, the cradle to gate impacts of the FU consist of the impacts from mining cobalt, and all further processes that are required to obtain 1kg cobalt sulfate. The results of the LCA provide thus the environmental impacts that are caused by producing 1kg cobalt sulfate.

## 2.2 Inventory Modeling

The inventory analysis includes and quantifies all flows for energy, materials, emissions, waste, etc. that occur within the system boundary of the FU. In-going and out-coming flows are distinguished, but all of them are scaled according to the amount that is required or caused by in relation to the functional unit (International Organization for Standardization, 2006). Continuing the above example, the life cycle inventory for the FU 1kg cobalt sulfate provides answers to the question “How much cobalt ore, energy, . . . , and sulfuric acid is needed to produce 1kg cobalt sulfate?” “What are the by-products, waste, . . . , and emissions are caused by producing 1kg cobalt sulfate?”. If a process contains more than

one product, flows and the respective impact must be allocated to both the main product and the by-product. According to ISO14044, allocation should be avoided if possible. If allocation is unavoidable due to the given circumstances, allocation by partitioning is recommended. The main and by-products are assessed based on physical properties like produced mass ore volume, or through their respective economic value. Allocation factors, either based on mass or economically, define how much of the in-going flows and impacts are related to each output product. By means, all in-going flows, as well as waste and emissions are divided within the main and by-products. Mass allocation is based on physical properties and is thus the preferably allocation method. In some cases, economic allocation yields more realistic impacts and is thus a better option than mass allocation (International Organization for Standardization, 2006).

$$A = \begin{bmatrix} A_{ff} & A_{fb} \\ A_{bf} & A_{bb} \end{bmatrix} \quad (1)$$

The  $A$  matrix represents the requirement matrix which includes all elementary process flows that are required to in the value chain of the functional unit. As shown in Equation 1, the matrix consists of four submatrices which represent flows between  $f$  which stands for foreground, and  $b$  for background.  $A_{ff}$  presents flows within foreground processes. The foreground in general contains processes that are chosen by the author for the functional unit, but can be affected by e.g., choosing to model a different production route. Opposingly,  $A_{bb}$  presents flows within background processes that are typically given through a database and the author cannot influence them (United Nations Environment Programme, 2019).  $A_{bf}$  models processes that go from the background to a foreground process, an example could be ‘0.8 kg sulfuric acid’ that is required in the foreground process ‘sulfate production’ to produce the FU 1kg cobalt sulfate. In reverse,  $A_{fb}$  depicts flows from the foreground to the background, which is typically rare and thus,  $A_{fb}$  is equal to zero in most cases (Strømman, 2010).

## 2.3 Impact Assessment

Life cycle impact assessment describes the process of transforming the established inventory into quantified impacts for various impact categories. Impacts can

be analysed for a wide range of midpoint categories focusing on environmental impacts, or be aggregated to endpoint level to emphasize on the damage to e.g., ecosystem quality or human health (United Nations Environment Programme, 2019). The calculations follow the basic contribution analysis by Strømman, 2010 and explain the way from defining a functional unit to arriving at quantified midpoint impacts for each process. The inventory presents the process flows that are required for the functional unit. To arrive at total emissions of the FU, several linear matrix transformations and a background matrix are required.

$$x = Ax + y \quad (2)$$

$$\begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} = \begin{bmatrix} A_{1,1} & \cdots & A_{1,pro} \\ \vdots & \ddots & \vdots \\ A_{pro,1} & \cdots & A_{pro,pro} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} + \begin{bmatrix} y_1 \\ \vdots \\ y_{pro} \end{bmatrix} \quad (3)$$

Equation 2 denotes that  $x$  is the total output of the system and consists of the sum of the intermediate demand  $Ax$  and the functional unit, i.e. the external demand  $y$ . Equation 3 presents the same as Equation 2 in the dimensions of the inventory system where *pro* stands for all the processes that are defined in the requirement matrix. Thus, the dimensions of matrix  $A$  are (*pro*  $\times$  *pro*) which included both fore- and background. The total output  $x$  and intermediate demand  $y$  are given as a vector with dimensions (*pro*  $\times$  1). The total output  $x$  is required for further calculations and can be calculated by solving Equation 2 since the intermediate demand  $Ax$  and the external demand  $y$  are already defined.

$$x = (I - A)^{-1}y = Ly \quad (4)$$

Through matrix inversion and with the identity matrix  $I$ , Equation 2 can be solved for the total output. In the following,  $(I - A)^{-1}$  is depicted as  $L$  referring to the Leontief inverse. In order to solve the Matrix, all processes must be self-sustaining and the determinant must fulfill the Hawkins-Simon conditions, i.e. the determinant  $\det(I-A)$  must be greater than zero.

$$e = Sx = SLy \quad (5)$$

$$\begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} = \begin{bmatrix} S_{1,1} & \cdots & S_{1,pro} \\ \vdots & \ddots & \vdots \\ S_{str,1} & \cdots & S_{str,pro} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} \quad (6)$$

Matrix  $S$  is the stressor intensity matrix with the dimensions ( $str \times pro$ ) where  $str$  stands for stressor, a universal term for emissions. The  $S$  matrix is multiplied by the external demand vector  $x$ , to arrive at vector  $e$ , which presents the vector for stressors, related to the  $y$  vector is shown in Equations 5 and 6. To translate individual stressors into contributions to one more impact categories, characterization factors are required. These are contained in Matrix  $C$ , which is thus of the dimensions ( $imp \times str$ ), where  $imp$  represents the impact categories.

$$d = Ce \quad (7)$$

$$\begin{bmatrix} d_1 \\ \vdots \\ d_{imp} \end{bmatrix} = \begin{bmatrix} C_{1,1} & \cdots & C_{1,str} \\ \vdots & \ddots & \vdots \\ C_{imp,1} & \cdots & C_{imp,str} \end{bmatrix} \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} \quad (8)$$

To arrive at the total impacts  $d$ , Matrix  $C$  must be multiplied by the  $e$  vector as in Equation 7 and 8. The impacts are calculated for each midpoint impact category. Hence, the dimension of  $d$  is ( $imp \times 1$ ).

Especially in this study, understanding the impact contribution of individual processes is crucial. Equation 9 employs the matrices  $C$  and  $E$ , where matrix  $E$  can be derived from the  $e$  vector to provide impacts on a process level in the matrix  $D_{pro}$ .

Equation 10 calculates the  $E$  matrix that is further required for calculating  $D_{pro}$ . The  $x$  vector has been diagonalized and thus yields matrix  $E$  as depicted in Equation 11. Consequently, Equations 12 and 13 present the matrix  $D_{pro}$ , which presents impacts of each process for each impact category.

$$D_{pro} = CE \quad (9)$$

$$E = \begin{bmatrix} s_{1,1} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{str,1} & \cdots & s_{str,pro} \end{bmatrix} \begin{bmatrix} x_1 & 0 & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & x_{pro} \end{bmatrix} \quad (10)$$

$$E = \begin{bmatrix} e_{1,1} & \cdots & e_{1,pro} \\ \vdots & \ddots & \vdots \\ e_{str,1} & \cdots & e_{str,pro} \end{bmatrix} \quad (11)$$

$$D_{pro} = \begin{bmatrix} c_{1,1} & \cdots & c_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & c_{imp,str} \end{bmatrix} \begin{bmatrix} e_{1,1} & \cdots & e_{1,pro} \\ \vdots & \ddots & \vdots \\ e_{str,1} & \cdots & e_{str,pro} \end{bmatrix} \quad (12)$$

$$D_{pro} = \begin{bmatrix} d_{1,1} & \cdots & d_{1,pro} \\ \vdots & \ddots & \vdots \\ d_{imp,1} & \cdots & d_{imp,pro} \end{bmatrix} \quad (13)$$

## **3 Case description**

### **3.1 Goal and Scope**

The conducted LCA is conform with the methodology and standards of ISO14044 (International Organization for Standardization, 2006). The goal of this LCA is to assess the impact of battery-grade materials produced in Norway in comparison to different regions. The results are relevant for both industry and academic research as well as policy making, to provide quantified impact scores and indicate potentials to reduce the impact of battery-grade material production by varying mining and production regions. The system boundary is cradle-to-gate, modeling the impacts from mining and ore processing, metal refining and the sulfate production. Under this scope, detailed life cycle inventories for the scenario of producing in Norway are established for the three respective functional units: 1 kg Nickel sulfate (FU1), 1kg Cobalt sulfate (FU2) and 1kg Manganese sulfate (FU3). To provide high data quality and novel data sets, the aggregated value chains consist of industrial data to the highest possible extent. In cases of non-available data, database processes are chosen and altered to better match the respective process. Three independent LCAs for the respective functional units provide environmental impacts on a midpoint level for producing in Norway. A total of nine further LCAs is conducted based on the established life cycle inventories to provide harmonized results for varying geographic regions. Three LCAs per functional unit are conducted to analyse the impact of regional electricity mixes for distinct mining-producing scenarios.

### **3.2 Inventory Modeling**

A crucial part of a LCA is the life cycle inventory (LCI). As depicted in Figure 3.1 detailed life cycle inventories for the battery-grade materials nickel-, cobalt- and manganese sulfate are developed. Each inventory is divided in the processes of mining and ore processing, metal refining and sulfate production which allows deeper analysis in the impact assessment.

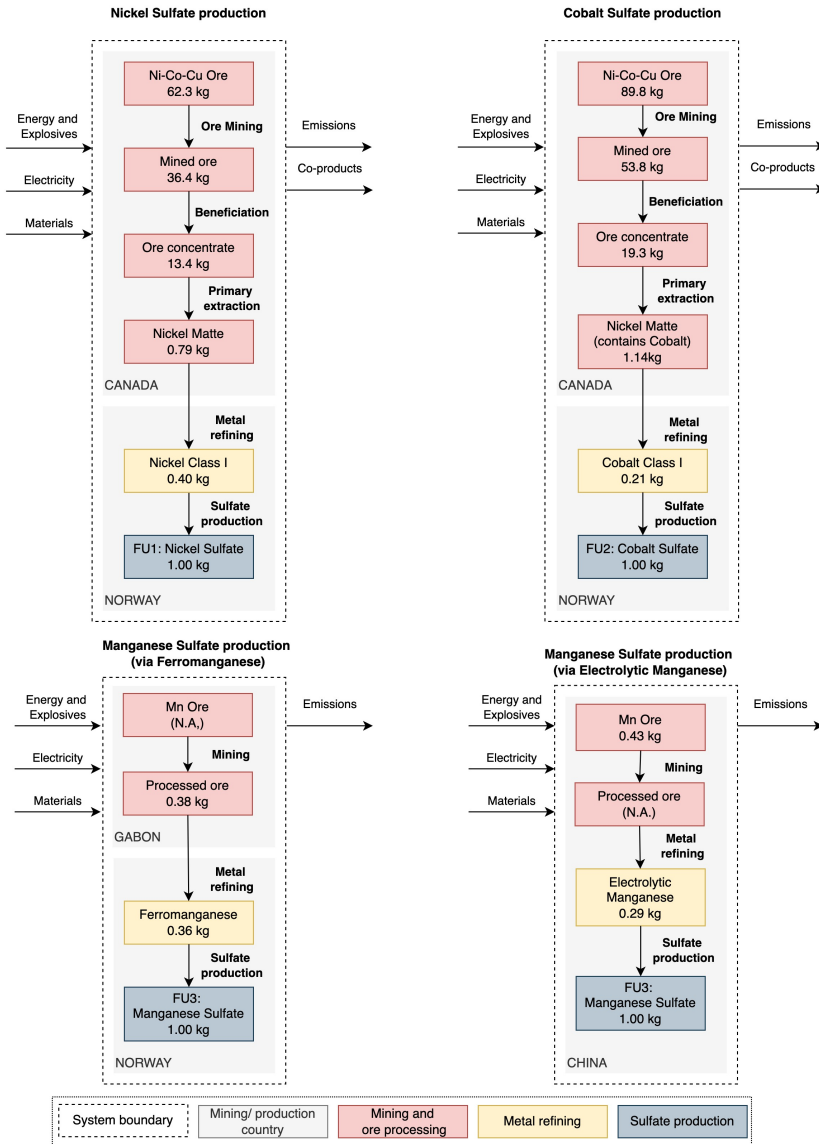


Figure 3.1: Flowchart, system boundary and material flows for the established life cycle inventories to produce nickel-, cobalt- and manganese sulfate.

The modeled value chains present production routes that consider mining and ore processing in either Canada for nickel and cobalt, or Gabon for manganese, while the metal refining and sulfate production takes place in Norway. Focusing on the implementation of industrial data, the production outputs and emissions from Norwegian metal refining present the core of the inventory. Glencore Nikkelverk produces nickel class I and cobalt class I, while Eramet Souda manufactures ferromanganese. Through ‘Norske Utslipp’, an initiative by the Norwegian Environment Agency, data on energy consumption, material output and direct emissions can be retrieved for the respective companies (Miljødirektoratet, 2017, Miljødirektoratet, 2020). From direct communication with Glencore Nikkelverk and Eramet, further information on the technicalities of production routes, intermediate- and output products, as well as details on the mining and ore processing process were retrieved. Furthermore, the starting point of the sulfate production process could be identified. Thus, a comprehensive value chain for both the mining and ore processing, and the sulfate production process could be established based on the provided industrial data for metal refining industrial data. The full life cycle inventories for producing nickel-, cobalt- and manganese sulfate present a main outcome of this study and attached in the Tables A.3 – A.5 in Appendix A.

### **3.2.1 Mining and Ore Processing**

#### **Mining and Ore Processing of Nickel and Cobalt**

After thorough analysis on the availability of literature and industry reports, the only available literature for mining and ore processing of both nickel and cobalt is from the Nickel Institute. The Nickel Institute compiled a detailed inventory for nickel class I based on primary industrial data for the nickel production based on the production year 2017 (Gediga and Boonzaier, 2020). Most cobalt reserves are in nickel-cobalt or nickel-cobalt-copper ores (Cobalt Institute, 2020). Thus, cobalt is typically mined as a by-product due to its low ore grade. To the best knowledge, there exists no publicly available inventory for cobalt mining and ore processing. As an appropriate alternative, the level of detail of the inventory published by the Nickel Institute allows to model the cobalt mining and ore processing as



a by-product of nickel value chain. The Nickel Institute inventory includes mining and ore processing, as well as the refining process with the functional unit of 1 kg nickel class I. Under the scope of this study, only the mining and ore processing procedure are of interest. The mining and ore processing process is further divided into the sub-processes, i.e., ore mining, beneficiation and primary extraction. Due to non-disclosure agreements, company- or process-specific data cannot be published. This is a crucial detriment of the inventory, as the impact of varying geographies and technologies is suspected to strongly affect the environmental impact of producing battery-grade materials. In consequence, the published inventory aggregates data from relevant mining countries, common production pathways and individual ore types to an average production process for manufacturing nickel class I. Despite this drawback, the given inventory provides the best available insight in the nickel- and cobalt mining and ore processing process.

In the established inventory that includes nickel and cobalt mining and or processing, over 150 elementary flows represent energy, electricity and material inputs, material outputs and direct emissions of the mining and ore processing process. This study follows the requirements of ISO14044 which advises to avoid allocation. In the context of mining however, the production of by-products must be considered. Allocation on physical properties is typically the preferred option, however, the discrepancy between low resource deposits and high market value indicates that mass-based allocation does not represent the situation. Therefore, economic allocation is chosen, and the required metal prices are retrieved as a long-term average and presented in Table A.1 in the Appendix.

$$AF_i = \frac{output_i \cdot price_i}{\sum_{x=i}^n output_x \cdot price_x} \quad (14)$$

Equation 14 clarifies the calculation of the allocation factor (AF) and the final AFs are summarized in Table A.2 in the Appendix. The *output* describes the annual production volume of the product in kg, the *price* is given in \$ /kg. Variable *i* declares the respective product, while variables *i . . . n* present all output products, i.e. main- and by-products. The allocation factors for the mining and ore processing process are calculated thus result to be 82% Nickel, 10% Cobalt, 8% Copper, based on the output products of the inventory provided by the Nickel

Institute.

According to the Nickel Institute, the inventory considers averaged production values. The geographic coverage for nickel and cobalt mining and ore processing is assumed to be global, since China as the main Nickel producer was excluded, and mining and ore processing is distributed world-wide (Gediga and Boonzaier, 2020) (Cobalt Institute, 2020). The purpose of this study is to analyse the environmental impacts related to the production of battery-grade materials in Norway. Based on the material- and process flow of Glencore Nikkelverk's metal refining process, the modeled mining and ore processing process aims to best implement the complementary mining and ore processing process (Miljødirektoratet, 2017). The ore described in the inventory by the Nickel Institute is similar to that mined for Glencore. The ore is mined underground, sulfidic Ni-Co-Cu ore and thus, processes, material, energy- and electricity consumption are presumed to be similar. Glencore does not provide a specific ore grade, but the cumulative amount of 'valuable material' is 4% (Eik, 2022). Throughout the whole procedure of mining and ore processing, nickel and cobalt remain compounds in the mined ore (Glencore, 2022). As for the Nickel Institute, the mining and ore processing begins with ore mining from either lateritic ore sulfidic ores. Even though the market for lateritic ore is growing, only sulfidic ore can be processed into high-grade metals which are required in the battery industry (Stanković et al., 2020). Thus, the value chain established in this study has high potential to represent a realistic scenario under the aspect of battery-production and the focus is set on processing sulfidic ore.

Glencore's mining and ore processing, i.e. ore mining, beneficiation and primary extraction, takes places in Canada. After the ore mining process, sulfidic ore undergoes beneficiation where the mined ore is reduced to form nickel concentrate. In the final step of ore processing the concentrated ore is converted into nickel matte, which is then shipped to the Glencore Nikkelverk in Norway where it is refined. The primary extraction includes either hydro- and/or pyrometallurgic processes. In the case of Glencore, the primary extraction process is pyrometallurgical. The created inventory and Stanković et al., 2020 indicate that the primary extraction process is energy-intensive. Thus, the benefit of dividing the mining and ore processing process in three sub-processes allows deeper analysis in the impact assessment.

### **Mining and Ore Processing of Manganese**

To the best knowledge, no industrial inventory data is publicly available for manganese mining and ore processing. Thus, manganese mining and ore processing was modeled through a case-sensitive, ecoinvent-based life cycle inventory (Manjong et al., 2021). 30 elementary flows model the essential processes for energy, electricity and material inputs, as well as direct emissions of manganese mining and ore processing. The inventory values are scaled by factors describing the chosen region, ore grade and mining type. Under the scope of modeling Eramet's value chain to produce ferromanganese in Sauda, Norway, the inventory by Manjong et al., 2021 is adapted.

Strongly different to nickel and cobalt deposits, the ore content of manganese ores is typically between 35% and 50% which indicates higher efficiency during the mining process and a thus, lower energy consumption. To produce ferromanganese, a specific blend of manganese ore types is required. For the case of Eramet, several metallurgical ores are required, which to the most, are mined in open-cast mines in Gabon (Haaland, 2022). The ores undergo beneficiation, i.e. crushing, screening and potentially washing (Olsen, Tangstad, and Lindstad, 2007). Eramet's ore composition, as well as mining and ore processing procedure were analysed but due to limited resolution of the data, Manganese ore mining process was modeled as a 'black box' in the life cycle inventory.

### **3.2.2 Metal Refining**

Industrial or academic life cycle data on refining the three analysed battery-grade materials is generally sparse or lacks transparency. That is why the following environmental data provided by the Norwegian Environment Agency (Miljødirektoratet) is of high value. It provides concise and detailed emission- and production data for domestic companies on the website 'Norske Utslipp'. Under the scope of creating a Norwegian-based value chain, industrial data on metal refining by Glencore and Eramet builds the core of the inventory for nickel-, cobalt- and manganese sulfate. Mining and ore processing, metal refining and sulfate production as the main processes are connected to form a coherent value chain for each material: Thus, the level of detail of the processed data from Norske Utslipp and the transparency of the developed inventory contribute to fill the research gap on the value-chain of the three battery-grade materials.

### **Refining to Nickel Class I and Cobalt Class I**

Glencore Nikkelverk in Norway as part of the global Glencore group is 'one of the major nickel producers in the western world' (Nikkelverk, 2022). Consequential to the by-products in the above mentioned mining process, the refining of nickel typically includes cobalt, copper and other valuable materials as by-products. Glencore Nikkelverk's production mainly covers the production of high-purity nickel class I and cobalt class I, but also produces copper and sulfuric acid along the refining process. Production, energy and emission data of Glencore Nikkelverk's is available through Norske Utslipp for the production year 2017 (Miljødirektoratet, 2017).

As for nickel- and cobalt mining, allocation is necessary for the metal refining process. This principle is chosen for two reasons, first to maintain methodological consistency within the thesis, and secondly since economic allocation best reflects the relationship to by-products. Allocation factors are calculated based on production data provided by Norske Utslipp and respective material prices as presented in Table A.1 in the Appendix. The calculation of the allocation factor AF as in analog to Equation 14, but furthermore including sulfuric acid as a by-product. The allocation factors are summarized in Table A.2 in the Appendix and calculate to 81% nickel, 9% cobalt, 9% copper, and 1% sulfuric acid.

The elementary flows in the established life cycle inventory for nickel and cobalt metal refining are based on data from Glencore Nikkelverk retrieved through Norske Utslipp (Miljødirektoratet, 2017). For both nickel and cobalt refining, the inventories consider each 80 elementary flows for energy inputs, material outputs and direct emissions to air and water. The refining process for nickel and cobalt from nickel matte is modeled as a 'black box' due to limited data resolution, but can be distributed in ore refining, solvent extraction, and electrowinning. First, the nickel matte undergoes a chlorine leaching process to dissolve nickel and cobalt. Under the solvent extraction process, copper and other impurities are selectively removed. In the final step, nickel class I is produced by electrowinning with a purity of 99.99%. Also through electrowinning, yet in a distinct process, Glencore produces cobalt class I with a purity of 99.98%. The overall refining process of nickel and cobalt is of high complexity but has followed the same principle over decades (Stensholt, Lund, and Zachariasen, 1986).

### **Refining to Ferromanganese**

Manufacturing nearly 250,000 tons of ferromanganese in 2021, the production volume of Eramet in Sauda, Norway, is significant and sees strong growth over the last years. Different to the steel industry, which is the main consumer of ferromanganese that contains 72% Mn, the battery-production requires high-purity metals. According to Eramet, the content of manganese in ferromanganese can be further increased, to reach a sufficient level of purity with relatively low additional energy input. Currently, the refining of ferromanganese is not economically profitable, but feasible from a technological point of view (Brozek, 2022). This study addresses the environmental impacts of potential battery-grade material production in Norway and since this has not been researched before, the availability of data is limited. For that reason, key-assumptions are required and thus, the technological viability is assumed to be more important than the economic viability. Since ferromanganese is the major output product, no allocation is required.

The elementary flows in the established life cycle inventory for manganese refining are based on data from Eramet Sauda retrieved through Norske Utslipp (Miljødirektoratet, 2020). The inventory considers 76 elementary flows for energy inputs, material outputs and direct emissions to air and water. After being mined in Gabon, the processed ore is blended at the plant in Sauda, Norway. Achieving the exact chemical composition of ferromanganese as a product requires a precise blend of different ores and advanced technology. After blending, the ore is transferred to electric furnaces. Coke is added to reduce the ore, i.e., to remove oxygen and impurities in the ore. In the consequent process step of the smelting process, carbon is removed, and ferromanganese is obtained in a ladle (Eramet Norway, 2022). The process behind refining manganese is complex and is subject of continuous innovation which makes it difficult to draw detailed conclusion regarding the refining process (Haaland, 2022).

### **3.2.3 Sulfate Production**

#### **Producing Nickel Sulfate**

According to literature, the production of nickel sulfate can be achieved in various ways Independence Group NL, 2021. The Nickel Institute provides inventory data for producing nickel sulfate from nickel intermediates, representing the industrial average (Gediga and Boonzaier, 2021) while a feasibility study published by the

Independence Group NL, 2021 presents a direct production from sulfidic ore. The Independence Group NL, 2021 furthermore present a number of established pathways to produce nickel sulfate. Amongst these is also the production of nickel sulfate from nickel class I, which is produced at the Glencore Nikkelverk. To the best knowledge, no industrial inventory data is publicly available for the sulfate production process from nickel class I. Ecoinvent provides a dataset for the production of nickel sulfate from nickel class I and chosen to be the most representative available data (Wernet et al., 2016). Since the production is considered to take place in Norway, the dataset was adapted to the Norwegian electricity mix.

To validate the results of this study, value chains for the production of Nickel sulfate are created based on reported literature. Except for the GREET model (Dai et al., 2019) and the production of nickel sulfate through nickel intermediates by the Nickel Institute (Gediga and Boonzaier, 2021), literature only reports impacts from the mining and ore processing and metal refining stages. Thus, the sulfate production process is added to complete the value chain and allow comparison. The sulfate production process for respective literature is based on the same ecoinvent inventory as the case of Norwegian production, while the electricity mix is regionalized according to the respective study.

### **Producing Cobalt Sulfate**

The data availability for cobalt sulfate production is rather limited but indicates that there exist several ways to produce cobalt sulfate. Rinne, Elomaa, and Lundström, 2021 present a process-model for producing cobalt sulfate from cobalt sulfide, while Pell and Tijsseling, 2020 provide an inventory for producing cobalt sulfate from cobalt hydroxide in the company First Cobalt. T. Zhang et al., 2021 and the GREET model by Dai et al., 2019 provide results, but no inventory for the production of cobalt sulfate, and furthermore, no ecoinvent dataset is available. This study aims to rely on industrial data to the highest possible extent. Thus, the inventory by First Cobalt is chosen to model the cobalt sulfate production process.

In the modeled process, cobalt hydroxide is replaced by cobalt class i. This is done stoichiometrically. First, the Co-content in cobalt hydroxide that is required to produce 1 kg cobalt sulfate is calculated. Secondly, the Co-content in cobalt class I is calculated. Based on the two values, the cobalt class I inventory is

scaled stoichiometrically and thus, provides the amount of cobalt class I required to produce 1 kg cobalt sulfate. Crundwell, Preez, and Knights, 2020 state that cobalt hydroxide is an intermediate product in the early stage of the cobalt refining process. The cobalt refining process is energy intensive and thus, stoichiometric scaling of cobalt class I to the intermediate product cobalt hydroxide, in the worst case, yields an overestimation of impacts. The electricity consumption in the process is adapted to fit the Norwegian electricity mix.

Some of the available publications provide LCA results for cobalt sulfate that include mining and ore processing, metal refining and sulfate production. However, other publication only provide impacts related to mining and ore processing and metal refining. For these cases, the just explained inventory by Pell and Tijsseling, 2020 is added to complete the cobalt sulfate value chain, while the electricity mix is, again, regionalized to the respective study.

### **Producing Manganese Sulfate**

The availability of manganese-related literature and inventory data is found to be low, which also accounts for the sulfate production process. To the best knowledge, no public data is reported and thus, the ecoinvent process for producing manganese sulfate from manganese oxide is chosen as the closest available approximation. The approximation is analog to that of producing cobalt sulfate from cobalt hydroxide. Figure 3.1 provides two inventory options for the production of manganese sulfate.

The first option, bottom left in Figure 3.1 presents sulfate production from ferromanganese, while the second option, bottom right in 3.1, models production from electrolytic manganese. Analog to the cobalt sulfate production, these inventories were as well scaled stoichiometrically regarding the Mn-content. Both inventories share the same process inventories, but the material flows between the processes are distinct as electrolytic manganese has a higher Mn-content than ferromanganese.

Thus, both options rely on the initial inventory which considers sulfate production from manganese oxide.  $MnO_2$  is chosen as an intermediate product of the manganese refining process which is, relatively speaking, energy intensive. Stoichiometric scaling of the ferromanganese inventory to match the manganese sulfate content could therefore lead to an overestimation of impacts, rather than an underestimation. As for nickel- and cobalt sulfate, published literature often

reports only impacts from the mining and ore processing and refining process. To allow comparison, the manganese sulfate value chain for respective literature is completed by adding the just explained inventory. The electricity mix is adjusted to each country or the global average accordingly.

### **3.2.4 Regional Variability of Electricity Mixes**

A typical NMC-cathode consists mainly of the three analysed battery-grade materials nickel-, cobalt- and manganese sulfate. Dunn, James, et al., 2015 concludes that the impact caused by the cathode contributes significantly to the total impact of a lithium-ion battery as it requires high amounts of energy and electricity. China is the primary manufacturer of batteries, which includes 70% of the world's battery cathode production (International Energy Agency, 2022) (Wang and Yu, 2021). On the other hand, Europe is second highest in the world's battery sales and particularly Norway presents the highest BEV per capita index in Europe while the market is growing strongly (Regjeringen, 2022). China's electricity mix is dominated by burning fossil fuels while Norway's electricity mix strongly relies on renewable sources (International Energy Agency, 2020). Thus, the overall environmental burden of battery-grade materials can potentially be reduced by shifting their production to countries with low-carbon electricity. While the production country of battery-grade materials can be chosen freely, the mining and ore processing is bound to countries with high ore deposits. To enhance the robustness of this study and the obtained LCA results, the established life cycle inventories for nickel-, cobalt- and manganese sulfate are regionalized as follows. The U.S. Geological Survey provides a list of major mining- and producing countries for nickel, cobalt and manganese. Based on this list, countries with the highest share in mining- and producing were selected for individual scenarios to produce nickel-, cobalt- and manganese sulfate. Three scenarios per battery-grade material are developed and a LCA is conducted for each regionalized scenario. Regionalization in this case means that the electricity mix in the life cycle inventory is adapted to the respective country, while the rest of life cycle inventory remains constant.



### **3.3 Impact Assessment**

The Life Cycle Impact assessment is conducted through the matlab-based in-house LCA software Arda which follows the linear, basic contribution analysis which is explained in the methodology in Section 2 (Strømman, 2010). The foreground matrix defines the main process flows which directly required for the functional unit, in this case mining and ore processing, metal refining and sulfate production. Processes and Stressors that contribute to foreground processes, are assigned representative ecoinvent 3.7 background processes. The LCA results provide impacts for foreground individual processes, as well as the structural path analysis for 18 midpoint impact categories. In this study, the ReCiPe V12 2016 method was selected. To be consistent with other publications, the hierarchist cultural perspective was chosen as a default model (Aitor Acero and Ciroth, 2015).

## **4 Results and Analysis - Norway as a producing country**

Life cycle inventories for producing three battery-grade materials, nickel sulfate, cobalt sulfate and manganese sulfate, were modeled for the main process stages mining and ore processing, metal refining, and sulfate production. The results of the conducted LCAs in each section are presented per Functional Unit, i.e. 1 kg nickel sulfate, 1 kg cobalt sulfate and 1 kg manganese sulfate. Furthermore, the countries which hold the processes of metal refining and sulfate production are also referred to as 'producing countries'.

In Section 4.1 both relative and absolute impacts of producing nickel- cobalt- and manganese sulfate are presented and analysed for all ReCiPe 2016 V12 midpoint impact categories. The full dataset for the impacts of nickel-, cobalt-, and manganese sulfate production is attached in Tables B.1 – B.3.

The scope of this thesis is do identify options to reduce the impact of the battery production. The conducted LCAs consider production in Norway and quantify impacts for each of the three major process steps of the value chain for each material. In order to validate the study, the resulting impact scores are taken as a baseline and benchmarked to pertinent literature which is presented in Section 4.2.

Most publications on battery-grade material production provide LCA results for GWP and results can be found for the impact categories TAP and PMFP. GWP as an impact category strongly captures the decarbonisation efforts of battery-grade materials. The GWP impact category provides impacts measured in 'kg  $CO_2$  equivalents', which quantify the respective contribution to climate change (Huijbregts et al., 2017). Furthermore, the resulting impacts of this study will set side by side with respective literature values. Comparing impacts requires the same impact category and unit. Hence, this study emphasizes on analysing the GWP impact of nickel-, cobalt- and manganese sulfate. As a foundation for future comparison of non-GWP impacts, process-based impacts for this study and aggregated literature-based value chains are compared in Figure B.1 and Figure B.2 in Appendix B.

GWP impacts vary within distinct mining- and producing countries of each of the

three battery-grade-materials. A significant potential driver for these discrepancies is the carbon intensity of the regional electricity mix. Thus, the effect of regionalizing mining- and producing scenarios on the change in GWP is analyzed. Results from 4.2 are taken as a baseline scenario and geographically distinct scenarios are modeled based on the established inventories., these variabilities are analysed in Section 4.3.

## 4.1 Environmental Impacts

### 4.1.1 Nickel Sulfate

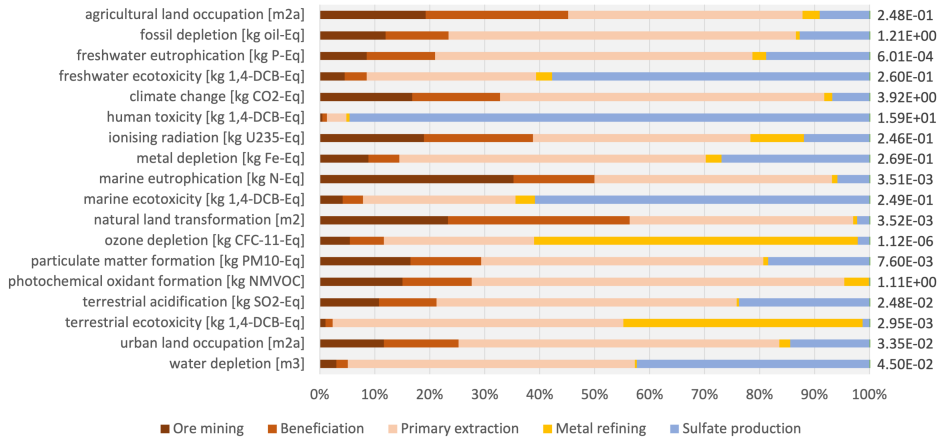


Figure 4.1: Impact of producing nickel sulfate on several midpoint impact categories showing the individual contribution of the processes mining and ore processing (divided in primary extraction, beneficiation and ore mining), metal refining, and sulfate production.

Figure 4.1 presents the environmental impact of individual processes related to the nickel sulfate production for multiple ReCiPe midpoint impact categories. In this study, the inventory divides the mining and ore processing in further sub-process ore mining, beneficiation and primary extraction. The three sub-processes take place in Canada and are operated by Glencore. Thus, Figure 4.1 shows that the

three-step mining and ore processing process has the highest relative contribution to most of the impact categories, except for impact category ozone depletion where metal refining has the largest impact, and toxicity-related impact categories. The nickel sulfate production as the final production process strongly contributes to impact categories related to toxicity and water depletion. Focusing on the non-toxicity impact categories, it is thus worth looking further into the impact of the mining and ore processing process. Out of the three sub-processes in mining and ore processing, primary extraction makes between 40% to 68% of the total impact in each category, excluding the impact categories just mentioned. The overall combined impact of ore mining and beneficiation is relatively small, except for agricultural land occupation (ALOP, 42.5%), marine eutrophication (MEP 49.9%) and natural land transformation (NLTP, 56.4%).

There is a tendency in all categories in which the impact from beneficiation is nearly equal to the the impact of ore mining in each impact category. The impact of metal refining, is less than 3% in all impact categories, except for the following impact categories: Ionising radiation (IRP, 10%) and especially for terrestrial ecotoxicity (TETP, 44%) and ozone depletion (59%). The impact of the last process step, the production of nickel sulfate, varies within the different impact categories. Sulfate production contributes less than 20% of the total impact for most categories, but is significantly higher for water depletion (WDP, 42%) and toxicity-related impact categories like freshwater ecotoxicity (FETP, 58%), marine ecotoxicity (METP, 61%) and accounts for 95% of the impact on human toxicity (HTP). Through the structural path analysis, direct 'water to air' emissions in the sulfate production cause the dominating impact on toxicity-related impact categories. The high impact of the sulfate production on water depletion can be explained by the tap water consumption in the synthesis of nickel sulfate.

Except for the toxicity-related categories, all impact categories imply that the main impact source is the primary extraction process. The reason for the high impact of the primary extraction can be found in the life cycle inventory. Primary extraction as a process has a high consumption of energy carriers and electricity which is the main reason for its high impact. Within the entire nickel sulfate production process, primary extraction has the highest consumption of fuels and electricity. Only for the metal refining process, the electricity requirement is higher while the need for energy carriers remains lower than that of primary extraction. The impact of metal refining and sulfate production is calculated with the Norwegian

electricity mix, while the mining and ore processing process is modeled with Canadian regional processes and electricity mix. The Norwegian electricity mix is known for being nearly fully renewable and causes therefore lower contribution to the individual impact categories. Thus, the electricity-intensive metal refining process in Norway has lower contribution to the impact categories, while the impact of the more carbon intensive electricity mix in Canada increases the impact of mining and ore processing (International Energy Agency, 2020).

### 4.1.2 Cobalt Sulfate

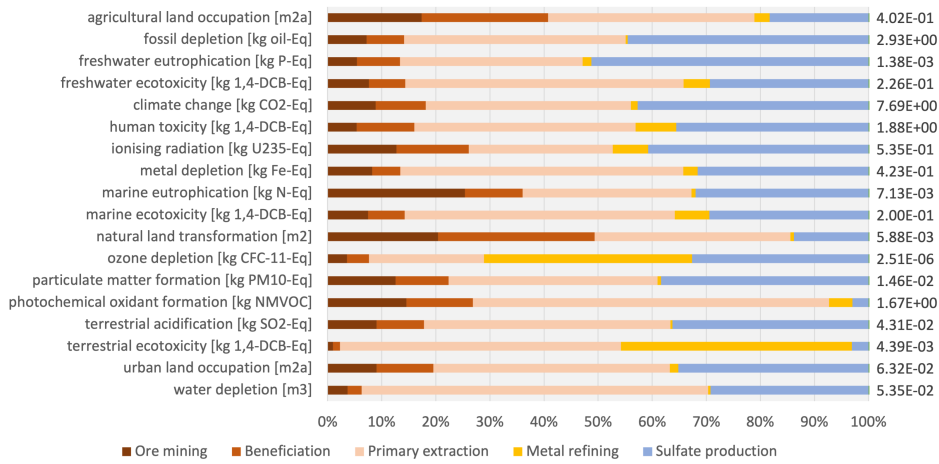


Figure 4.2: Impact of producing cobalt sulfate on several midpoint impact categories showing the individual contribution of the processes mining and ore processing (divided in primary extraction, beneficiation and ore mining), metal refining and sulfate production.

Figure 4.2 shows the environmental impact of individual processes of the cobalt sulfate production for multiple ReCiPe midpoint categories. As a general result, the relative impacts of producing cobalt sulfate are distributed similarly to the impacts of nickel sulfate. The major difference is that the relative impact of the sulfate production process is higher for cobalt sulfate. The figure shows that the mining and ore processing, and the sulfate production process have the major

impact in most of the midpoint categories. While for the major part of categories the highest impact stems from mining and ore processing, the major impact for the categories categories freshwater eutrophication (FEP) and ozone depletion (ODP) is from sulfate production and metal refining, respectively. Just as for the production of nickel sulfate, the terrestrial ecotoxicity impact of the metal refining process stands out with 43%. Out of the three sub-processes in mining and ore processing, primary extraction makes between 27% to 66% of the total impact in each category, excluding ozone depletion that is dominated by impacts from metal refining and sulfate production (ODP). For producing cobalt sulfate, the impact of ore mining and beneficiation is relatively small, except for agricultural land occupation (ALOP, 50%), marine eutrophication (MEP, 36%) and natural land transformation (NLTP, 49%). As for nickel sulfate, the impact from beneficiation is relatively similar to the the impact of ore mining in each impact category. The impact of the metal refining process is less than 7% in all impact categories. except for the impacts on ozone depletion (ODP, 38%) and terrestrial ecotoxicity (TETP, 43%). The structural path analysis indicates that ODP and TETP impacts are caused by hydrogen chloride and copper emissions to air, respectively. The impacts of the last process step, the production of cobalt sulfate, vary within the different impact categories. The impact of sulfate production on terrestrial ecotoxicity (TETP) and photochemical oxidation (POFP) is only 3%. For all other categories, the impact of the sulfate production varies between 14% and 51%, which is higher percentage in contribution compared to the impact of sulfate production for nickel sulfate.

For the production of cobalt sulfate, nearly all impact categories imply that the main impact sources are primary extraction and sulfate production. The reason for the high impact of primary extraction as a process is its high energy intensity and electricity consumption, affected by the Canadian electricity mix with a higher carbon intensity. The reason for the high impact of the sulfate production can as well be found in the life cycle inventory. Comparing the sulfate production process of cobalt sulfate and nickel sulfate, it can be seen the energy consumption 35% higher for cobalt sulfate which explains the difference in the relative distribution of impacts by process..

### 4.1.3 Manganese Sulfate

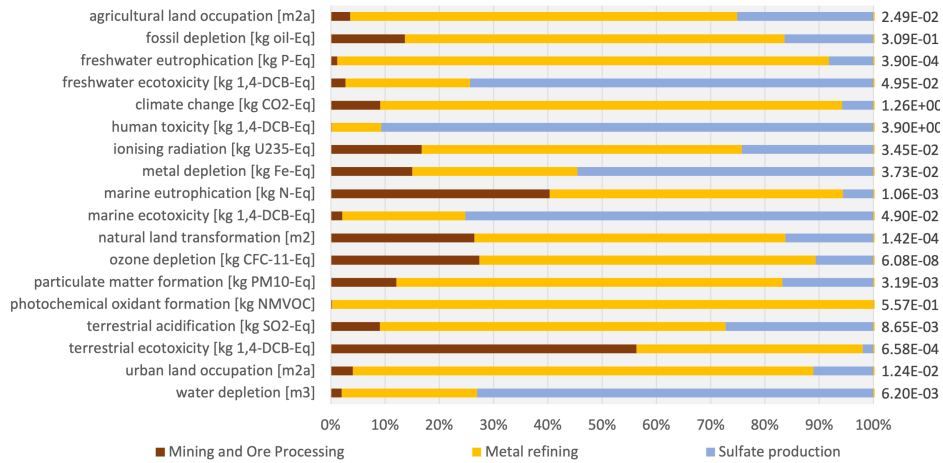


Figure 4.3: Impact of producing manganese sulfate on different midpoint impact categories showing the individual contribution of the processes mining and ore processing, metal refining, and sulfate production.

Figure 4.3 shows the environmental impact of individual processes of manganese sulfate production for multiple ReCiPe midpoint categories. Generally different from nickel- and cobalt sulfate, where the main impacts are from the mining process, the major contribution in producing manganese sulfate stems from metal refining and sulfate production in most categories.

Furthermore, figure 4.3 clarifies that the impact of mining and ore processing is relatively low, compared to the other two materials, but also compared to manganese metal refining and sulfate production processes, except for the impact categories terrestrial ecotoxicity (TETP) and marine eutrophication (MEP). The metal refining process of Ferromanganese states the major impact in nearly all impact categories. The impacts of metal refining on freshwater ecotoxicity (FETP), human toxicity (HTP), marine ecotoxicity (METP) and water depletion (WDP) are marginal for relatively low, as the main impact is caused by producing sulfate. The impact of the sulfate production process varies strongly within the different categories. By means, the highest impact of sulfate production as the final process

can be found for the categories freshwater ecotoxicity (FETP, 75%), human toxicity (HTP, 91%), marine ecotoxicity (METP, 75%) and water depletion (WDP, 73%). Oppositely, the impact of sulfate production on freshwater eutrophication (FEP), climate change (GWP), marine eutrophication (MEP), photochemical oxidant formation (POFP) and terrestrial ecotoxicity (FETP) is below 10% in each category. As for nickel sulfate, the structural path analysis shows that direct 'water to air' emissions in the sulfate production cause the dominating impact on toxicity-related impact categories.

The absolute values of each category show that the impacts of producing manganese sulfate are much lower than these of nickel or cobalt sulfate. Thus, the overall low impact of manganese mining and ore processing appears to be minor. The structural path analysis implies that the only two notable impacts of the mining and ore processing in TETP and MEP are caused by the diesel burnt in building machines. The electricity and energy consumption of the mining and ore processing process is relatively low. In addition, the regional electricity mix in Gabon causes lesser impacts as it consists of 82% renewable sources (International Energy Agency, 2020).

For the production of manganese sulfate, the metal refining process has a significantly high consumption of energy carriers compared to nickel- and cobalt sulfate, while the electricity consumption is slightly lower. Refined in Norway, the impacts caused by electricity consumption for manganese sulfate are minor, so that the consumption and burning of fuels causes the majority of the metal refining impacts. Even though the total impacts of manganese sulfate production are lower, the absolute impact caused by the refining of ferromanganese is higher compared to nickel- or cobalt class I refining.

## **4.2 Impact on Global Warming**

The Global Warming Potential one of the most discussed impact categories in LCA and highlights carbon-related impacts, especially from the energy- and electricity sectors, that contribute to climate change. Thus, the GWP is an adequate indicator to analyse the impact of energy and electricity consumption which has been found out to be the most relevant contributor in the production of the battery-grade materials nickel-, cobalt- and manganese sulfate.



## 4.2.1 Nickel Sulfate

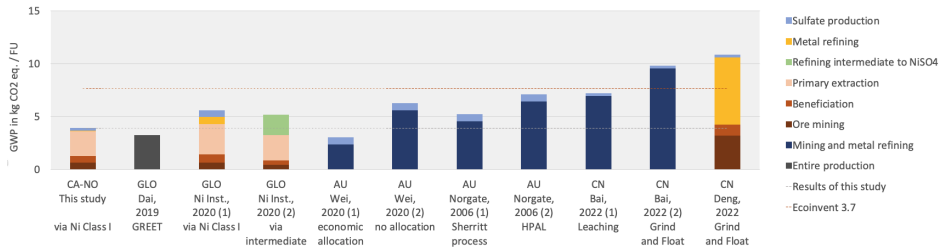


Figure 4.4: Global warming potential of producing 1kg nickel sulfate. The results of this study consider mining and ore processing in Canada and refining and sulfate production in Norway via nickel class I. This study is in direct comparison to the reference process of ecoinvent 3.7 and literature-based value chain models with varying geographic locations, production routes and allocation methods.

This study models the production of nickel sulfate for the three main production stages, mining and ore processing, metal refining to nickel class I, and sulfate production. The impacts for the production of nickel sulfate are shown in Figure 4.4 and analysed in the following. Out of the three analysed battery-grade materials, nickel sulfate is the one with the highest amount of available publications and life cycle data. It thus allows better comparison and validation of the resulting impacts obtained in this study. The impacts of the nickel sulfate value chain established in this study are benchmarked against available literature. Most of the available literature models the mining and ore processing, and metal refining processes but not the sulfate production. To complete the value chain of literature studies and allow cross comparison, the sulfate production process is modeled by a regionalized ecoinvent process i.e., using regional electricity mixes and processes instead of the generic values.

Apart from this study, two cases were found to be modeled in-depth. Data from the Nickel Institute for the global average, and a study by Deng and Gong, 2018 for China thus allow deeper understanding regarding the sources of the impacts along the value chain.

The results of this study assume mining and ore processing in Canada and metal

refining and sulfate producing in Norway which gives a total impact of 3.9  $kgCO_2eq$ . Mining and ore processing, which occurs in Canada, particularly the primary extraction, has the highest impact on Global Warming while ore mining and beneficiation have a lower contribution. In Norway, metal refining has nearly no contribution, and the impact of the sulfate production in Norway is relatively little. The life cycle inventory of the mining and ore processing process in this study is based on the inventory of the nickel class I production published by the Nickel Institute (Gediga and Boonzaier, 2020). It was altered to fit the chosen geographies and considers cobalt and copper as by-products in the form of economic allocation.

Case (1) of the Nickel Institute as just explained, presents the nickel sulfate production route via nickel class I. The impacts of the non-altered value chain sum up to 5.6  $kgCO_2eq$ . (Gediga and Boonzaier, 2020). Case (2) of the Nickel Institute models the impact of direct nickel sulfate production via nickel intermediates and results in 5.2  $kgCO_2eq$ . (Gediga and Boonzaier, 2021). In these two cases, the Nickel Institute aggregates different production routes, technologies and assumes the global average electricity mix. For this study, as well as case (1) and case (2) by the Nickel Institute which are modeled in depth-, mining and ore processing, especially primary extraction, has the highest impact. This study, and case (1) of the Nickel Institute are both via nickel class I and show a higher impact on the mining and ore processing, compared to case (1), the nickel sulfate production via nickel intermediates. The Nickel Institute averaged respective industry data for different nickel products, i.e. there are different data sets in the inventories for case (1) and case (2) which are likely to be the reason for the varying total impact in the two presented cases. A reason for the lower impact in the mining and ore processing stage of this study compared to case (1) can be related to the difference in electricity mixes, and the economic allocation that is applied in this study. The Norwegian metal refining and sulfate production impacts are significantly lower than the reported impacts by the nickel Institute. The metal refining impact in Norway is marginal. Thus, the variance of this study compared to case (1) is likely to be caused by the lower carbon intensity of the Norwegian electricity mix. Within the two cases of the Nickel Institute, the production of nickel sulfate from nickel intermediate accounts for a higher impact than the sulfate production from nickel class I, but a lower impact in total as the combined refining-sulfate production processes is lower for intermediates than for the case of producing via nickel class I. Sulfate production has a relatively low impact in both, this study

and case (1), which indicates the sensitivity to electricity mixes as Norway has a lower impact.

The results that were just discussed partially differ to the study by Deng and Gong, 2018 in China. Compared to the studies just mentioned, Deng and Gong, 2018 report slightly higher impacts in the mining and ore processing process, but in addition  $6.3 \text{ kgCO}_2\text{eq.}$  caused by the metal refining, yielding a total impact of  $10.8 \text{ kgCO}_2$ . A plausible explanation for the high impact of metal refining can be the high carbon intensity of the Chinese electricity mix and different refining technologies. Other factors that might contribute to the high impact can be a difference in the emission-intensity of background data that was used for this study. Further details of this study's results are discussed later in this paragraph in direct comparison to other studies in China.

The following studies only report the total impact of the conducted LCA and can therefore not be discussed in-depth. Compared to a total of ten cases from the literature, only two cases score lower than this study. One of them is the GREET model by Dai et al., 2019, which arrives at  $3.3 \text{ kgCO}_2\text{eq.}$  This model has a production structure similar to this study, but is based on global inventory values. The other study is a mathematical model by Wei et al., 2020 based in Australia and arrives at  $3.1 \text{ kgCO}_2\text{eq.}$  Wei's model allocates impacts to by-products by applying system expansion and thereby reduces the impact of producing nickel. The relevance of allocation on the impact score becomes clear as Wei et al., 2020 furthermore presents the same case without allocation that results in  $6.3 \text{ CO}_2\text{eq.}$

With higher results than this study, and arriving at over twice of the impact if allocation is not considered, this contrast clarifies the complexity of modeling value chains as these with multiple outputs.

Based in Australia, Norgate, Jahanshahi, and Rankin, 2007 present two cases that distinguish between different pyrometallurgical (Sherritt Gordon process) and hydrometallurgical (HPAL) refining processes. Pyrometallurgical refining results in  $5.2 \text{ CO}_2\text{eq.}$ , while hydrometallurgical refining causes  $7.1 \text{ kgCO}_2\text{eq.}$  Comparing the results in Australia, the hydrometallurgical production route of nickel sulfate has the highest impact, followed by the model by Wei et al., 2020 without allocation and the pyrometallurgical Sherritt process by Norgate, Jahanshahi, and Rankin, 2007. The allocation scenario stated by Wei et al., 2020

provides a substantially lower impact that should be further discussed.

Another study is conducted by Bai et al., 2022, based in China it distinguishes between different refining routes. Two pyrometallurgical routes are compared, Nickel via leaching which causes  $7.2 CO_2eq.$ , and nickel via grinding and flotation which causes  $9.8 kgCO_2eq.$  As discussed earlier, the impacts reported by Deng and Gong, 2018 are higher than the results from Bai et al., 2022, which makes these two studies the ones with the highest impact.

The global ecoinvent 3.7 nickel sulfate production process is taken as a reference and is with  $7.7 kgCO_2eq.$  higher than the results of the majority of literature, including this study. In conclusion, the results for the GWP impact of producing nickel sulfate show a large variation between countries and the related carbon intensity of their electricity mix, allocation methods, production routes and potentially different ore grades. Only few studies report impacts for the individual process steps which makes it difficult to analyse and identify the main impact sources.

Aligned with the Gediga and Boonzaier, 2020 and Deng and Gong, 2018, the GWP results of this study indicate that primary extraction is the main contributors in nickel sulfate production. However, Deng and Gong, 2018 furthermore report high impacts in the metal refining process. The impact of the sulfate production process varies by country, but has a rather low contribution to GWP.

## 4.2.2 Cobalt Sulfate

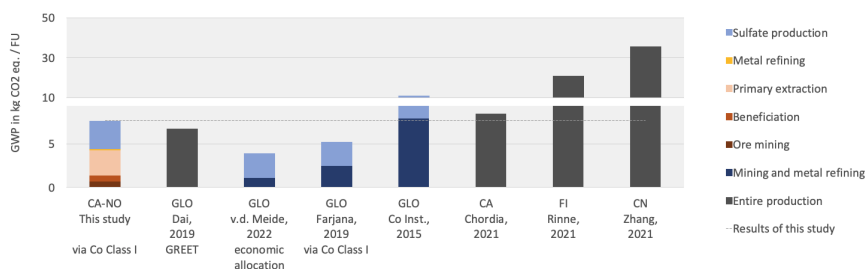


Figure 4.5: Global warming potential of producing 1kg cobalt sulfate. The results of this study consider mining and ore processing in Canada and refining and sulfate production in Norway via cobalt class I. This study is in direct comparison to literature-based value chain models with varying geographic locations, production routes and allocation methods.

This study models the production of cobalt sulfate in depth for the three main stages, mining and ore processing, metal refining to cobalt class I, and sulfate production. The impacts on Global Warming for the production of cobalt sulfate are shown in Figure 4.5 and analysed in the following. Generally, the data availability for the cobalt sulfate value chain is lower compared to production of nickel sulfate, but also variations in the resulting impacts are larger. Literature and industry represent total LCA results for mainly two cases: Either the entire cobalt sulfate production, or the mining and ore processing, and the refining process to cobalt metal. The availability of only single-score impacts makes it difficult to identify the main impact contributors within the different processes. To model the entire value chain of producing cobalt sulfate, sulfate production was modeled with industry data from Pell and Tijsseling, 2020 for the data sets that only cover the mining and ore processing, and metal refining processes. These cases indicate that the impact from mining and ore processing, and metal refining strongly varies between studies, while the impact from the sulfate production remains relatively constant for both geographies, Norway and globally. Results that were report for the entire cobalt sulfate value chain vary largely and no direct correlation can be identified within geographies.

For this study, cobalt mining and ore processing in Canada and refining and sulfate production in Norway is assumed which results in a GWP of  $7.7 \text{ kgCO}_2\text{eq.}$  per kg cobalt sulfate. Here, the major impact is caused by mining and ore processing, particularly primary extraction. Additionally, nearly half of the impact in the cobalt sulfate production is related to the sulfate production. The reason for the significant impact of sulfate production is the high consumption of natural gas as an energy carrier. The sulfate production process is less dependent on electricity, which explains why the related impact of the process is similar in the different geographies. However, the sulfate production process is scaled stoichiometrically and in combination with the taken assumptions potentially overestimating the resulting impact. The metal refining takes place in Norway and has a marginal contribution to GWP.

The GREET model by Dai et al., 2019 assumes mining in the Democratic Republic of the Congo, and global production of cobalt sulfate which results in  $6.8 \text{ kgCO}_2\text{eq.}$  A recently published study by Meide et al., 2022 presents impacts for aggregated primary production routes for global cobalt production. Using economic allocation, the impact results in  $3.9 \text{ kgCO}_2\text{eq.}$  As for the results by Wei for the production of nickel sulfate, there is a clear tendency of receiving impacts that are significantly lower than other studies when using allocation which must as well be considered in the interpretation of the results obtained by this.

The value chain based on the often-cited study by Farjana, Huda, and Mahmud, 2019 results in  $5.3 \text{ kgCO}_2\text{eq.}$  The study uses system expansion, but the transparency of the mining and metal refining processes is not publicly available. Furthermore, the Cobalt Institute provides a life cycle inventory for the mining and ore processing and refining of cobalt metal on a global average. Based on this inventory, a resulting impact of  $10.8 \text{ kgCO}_2\text{eq.}$  was estimated. Compared to other studies that consider the global average, the value chain based on the Cobalt Institute has a significantly higher impact. A plausible explanation for the high impact life cycle inventory that the compiled inventory likely covers a broad range of production routes. The study was published in 2015 and since then, there might have been innovations in technology and emission reduction measures that explain the variance compared to recently conducted studies.

Another study by Chordia, Nordelöf, and Ellingsen, 2021 suggests a total impact of  $8.5 \text{ kg CO}_2\text{eq.}$  with cobalt production in Canada. With primary data on refining

and a stoichiometric estimate of the sulfate production, the study by Chordia, Nordelöf, and Ellingsen, 2021 is very similar to the setup of this study. Given the differences of the Canadian and Norwegian electricity mix, the resulting impacts of these two studies are very similar and indicate good accuracy of this study.

Two more studies report distinct results that suggest impact up to ten times higher relative to the just mentioned studies. The process model by Rinne, Elomaa, and Lundström, 2021 includes mining and ore processing, hydrometallurgical metal refining and sulfate production in Finland and scores 20.9  $kgCO_2eq$ . A reason for the relatively high impact could be the low ore grade (1.35% Co) and the hydrometallurgical refining which is likely to cause higher impacts on GWP as experienced in the different metal refining routes of nickel sulfate that were discussed in the previous paragraph. Like Rinne, Elomaa, and Lundström, 2021, T. Zhang et al., 2021 reports a study on the production of cobalt sulfate in China which results in 35.6  $kgCO_2eq$ . With 0.4% Co, the ore grade is significantly lower, and thus likely to increase the impact from mining. As Rinne, Elomaa, and Lundström, 2021, the model by T. Zhang et al., 2021 also considers impact-intensive hydrometallurgical refining. In their paper, T. Zhang et al., 2021 indicate the relevance of the high carbon intensity of the Chinese electricity mix which is yet another parameter to yield a higher total impact score.

In conclusion, there is no ecoinvent process available for the cobalt sulfate production. The impact score for producing cobalt sulfate obtained in this study is aligned with the most recent and similar study by Chordia, Nordelöf, and Ellingsen, 2021. Both studies, Chordia, Nordelöf, and Ellingsen, 2021 and this study lie between the extreme ends of high results in China and Finland, and otherwise low results for global value chains. While the variation in results is significant for the case of cobalt sulfate, the parameters that potentially influence the impact are the same as for the production of nickel sulfate. These are the carbon intensity of the regional electricity mix, allocation methods, production routes for the metal refining process, and especially for cobalt ores, the level of the ore grade.

### 4.2.3 Manganese Sulfate

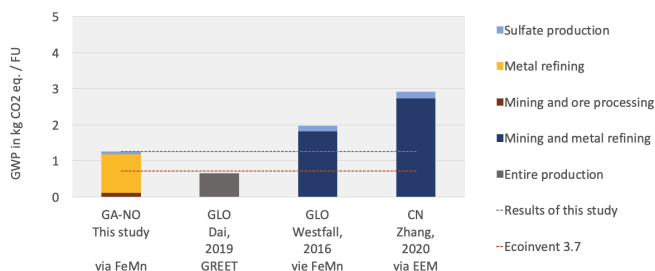


Figure 4.6: Global warming potential of producing 1kg manganese sulfate. The results of this study consider mining and ore processing in Gabon and refining and sulfate production in Norway via nickel class I. This study is in direct comparison to the reference process of ecoinvent 3.7 and literature-based value chain models with varying geographic locations, production routes and allocation principles.

The calculated impacts for the production of manganese sulfate are shown in Figure 4.6 and analysed for the three main stages, mining and ore processing, metal refining, and sulfate production. For the mining and ore processing process, an ore grade of 44% and underground-mining is assumed with a beneficiation recovery efficiency of 95%. The data availability for the manganese sulfate value chain is very scarce compared to nickel- or cobalt sulfate, and furthermore the available data available varies largely. For this study, mining and ore processing in Gabon and refining and sulfate production in Norway are assumed which results in total to a GWP of 1.3  $kgCO_2eq$ . Strongly different to nickel- and cobalt sulfate, the absolute impact of manganese sulfate is significantly lower. Nearly the entire GWP impact stems from refining ore to ferromanganese. The mining and ore processing only takes in a minor role regarding the impacts from the production of manganese sulfate. The impact of the sulfate production is relatively low but varies within the different geographies and related electricity mixes. Thus, the impact of sulfate production is lower in Norway than in China or the global average. Out of the three studies available, only the GREET model by Dai et al., 2019 provides a full value chain, yet single-score impact to produce manganese sulfate based on the global average. The results suggest an impact of 0.7  $kgCO_2eq$ . Westfall et al., 2016 provide another study on the production of Ferromanganese for the global



average. The created value chain based on Westfall et al., 2016 suggests an impact of  $2.0 \text{ kgCO}_2$ . A slightly different production route via electrolytic manganese is reported by R. Zhang et al., 2020 who suggest a total impact of  $2.9 \text{ kgCO}_2$  for China.

Similar to nickel- and cobalt sulfate production, the studies conducted in China yield the highest impact scores. While the production route of electrolytic manganese is like to vary compared to that of ferromanganese, other factors such as ore grade, technology, life cycle data base, and especially the Chinese electricity mix might as well contribute to an increase in impact. The resulting impact of this study lies in between the impact scores reported by literature. The global ecoinvent 3.7 manganese sulfate production process is taken as a reference, which is with  $0.7 \text{ kgCO}_2 \text{ eq.}$  closest to the impact of the GREET model, and lower than the impacts of this study. As for nickel- and cobalt sulfate, the results of the GREET model by Dai et al., 2019 are amongst the lowest compared to literature and as consistently lower than the results of this study. This study is in its structure most similar to Westfall et al., 2016 out of the available studies as both value chains produce manganese sulfate via Ferromanganese. In the case of this study, mining and ore processing takes place in Gabon and has little contribution to the total impact score. Westfall et al., 2016 does not specify where the mining and ore processing takes place or which mining type is considered, i.e. below- or above ground. Furthermore, the presumed ore grade and the carbon intensity of the electricity might be less beneficial than the assumed values for the case of mining and ore processing in Gabon, and thus yield a higher impact.

#### **4.2.4 Comparison to GREET and Ecoinvent**

The GREET model by Dai et al., 2019 is the sole provider for the impacts of all of the three battery-grade materials. It thus allows comparison of the total impacts, but the 'black box' disables deeper analysis on a process level. Furthermore, ecoinvent as a major database provides some of the relevant processes and respective impacts. In the case of the nickel sulfate production, no further information is published by the GREET model, except that the reaction to form nickel sulfate is calculated stoichiometrically and without the use of energy as it is exothermic. In this study, energy-consuming stoichiometric reactions in the sulfate production are assumed and based on the ecoinvent process. The production process of Nickel sulfate,

including mining and ore processing and refining, modeled in ecoinvent yields a GWP impact that is above most of values reported by literature, including this study. Considering the differences in electricity consumption that indicate lower impacts related to the lower carbon-intensity in Norway, this study can be seen aligned closely to the GREET model. The difference to the ecoinvent impact is significant. However, there is no further information available and the ecoinvent process which makes a deeper understanding of the variance non-viable.

To produce cobalt sulfate, no process is available in ecoinvent. The GREET model and this study yield similar results considering the following differences: For GREET, a cobalt-copper mine in the Democratic Republic of the Congo is considered instead of Nickel-Cobalt-Copper mine in Canada as in this study. The whole production process in GREET is via leaching and similar to this study. The slightly lower impact of the GREET model is likely to be due to the differences in the ore composition and grade, as well as the low-carbon electricity mix in DRC in the mining and ore processing stage which can be beneficial to lower the GWP impact of cobalt sulfate.

For manganese sulfate, GREET data is only available from 2019 and is lower than related literature, including this study. In 2021, the GREET process flow of manganese sulfate has been revised by the authors. The conclusion was that the ore grade in previous models was assumed too high i.e., the impacts of manganese sulfate were underestimated. Considering this revision, the results from this study and the GREET model for manganese sulfate are in line. Opposing to nickel sulfate, the impact of ecoinvent to produce manganese sulfate, including mining and ore processing and metal refining, is nearly the same as the GREET score and lower than reported impacts by the literature, including this study. Again, no process description is available for the ecoinvent process which restricts further understanding of the significantly higher score.

### **4.3 Regional Variability of Electricity Mixes**

Section 4.2 concludes a significant variation in the resulting impacts for all three battery-grade materials. There are multiple reasons to cause the contrasting impacts. Methodological variation is a crucial driver, i.e., how detailed inventories are constructed; which database is used for the background; whether it is primary

industrial or secondary data, a mathematical or process model and which software is used to conduct the LCA and analyse the impact. Another source of varying impact results can be the variation of ore grades and efficiencies in the mining and ore processing process, the type of production route and technology used in the metal refining process, and in most cases, the carbon intensity of the regional electricity mix.

Especially the varying electricity mix within different countries appears to have a significant effect on the production impact. The detailed inventories for nickel-, cobalt- and manganese sulfate production that were established in the scope of this thesis, provide insight in the respective processes along the value chain.

For each of the analysed materials, metal refining and sulfate production in Norway are shown to have a relatively low total impact on GWP thanks to the low-carbon electricity mix in Norway (International Energy Agency, 2020). The results also show that the impact of mining and ore processing can vary largely. The mining and ore processing process is limited to take place in the countries with high ore deposit, while the electricity-intensive metal refining and sulfate production processes mostly happen in industrialized countries. In order to produce harmonized results with a consistent life cycle inventory, three scenarios were developed for each battery-grade material. The initial combination of Canada–Norway for nickel- and cobalt sulfate, and Gabon–Norway for manganese sulfate as mining and ore processing–producing countries is set to be the baseline of these scenarios. The electricity mixes are regionalized for each scenario and combine a common mining country with a potential producing country.

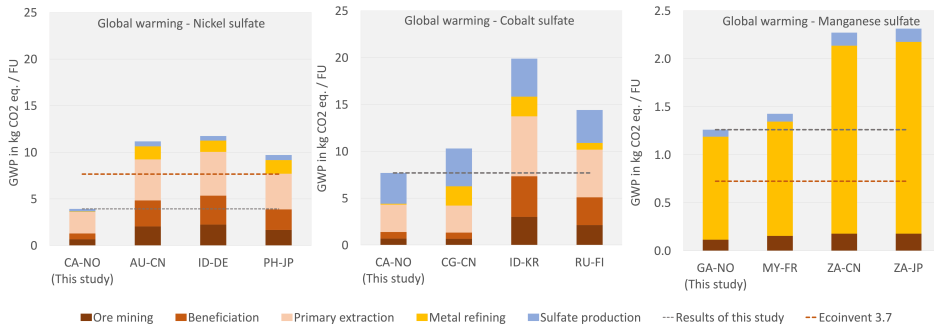


Figure 4.7: Impact of varying regional electricity on the global warming potential in comparison to the case of Norwegian metal refining and sulfate production.

### 4.3.1 Nickel Sulfate

The left graph in Figure 4.7 shows the three scenarios in comparison to the Canada-Norway production scenario for nickel sulfate. For the different scenarios, the main increase in impacts from nickel sulfate production can be seen in the mining and ore processing. Primary extraction still contributes most, but the increase in impact caused by beneficiation and ore mining is significant, and clearly proportional to the carbon intensity of the electricity mix. The total impact of the mining and ore processing process is  $3.6 \text{ kgCO}_2\text{eq.}$  for Canada,  $7.7 \text{ kgCO}_2\text{eq.}$  in the Philippines,  $9.2 \text{ kgCO}_2\text{eq.}$  in Australia, and with  $10.0 \text{ kgCO}_2\text{eq.}$  highest in Indonesia. While metal refining has a marginal impact in Norway ( $0.06 \text{ kgCO}_2\text{eq.}$ ), the impact increases significantly in Germany ( $1.2 \text{ kgCO}_2\text{eq.}$ ), China ( $1.4 \text{ kgCO}_2\text{eq.}$ ) and is highest in Japan ( $1.5 \text{ kgCO}_2\text{eq.}$ ). The impact of sulfate production is relatively small for all scenarios, but slightly higher in non-Norwegian countries:  $0.3 \text{ kgCO}_2\text{eq.}$  in Norway,  $0.5 \text{ kgCO}_2\text{eq.}$  in China and Germany, and  $5.5 \text{ kgCO}_2\text{eq.}$  in Japan. Comparing the different scenarios, Canada as a mining and ore processing, and Norway as a producing country have the lowest impact on GWP. Indonesia and Japan present the countries with the highest impacts on GWP. Compared to the results of Section 4.2, the sensitivity analysis yields generally higher impacts. Consequently, the obtained impacts are as well higher than the ecoinvent 3.7 process. In this section, constant factors for ore grade, production route and technology were assumed which, however, are likely to vary within the selected countries. Thus, the obtained results for

varying electricity mixes are of high relevance, but the just mentioned factors might further alter the local mining and ore processing, and further producing situation.

### 4.3.2 Cobalt Sulfate

For the cobalt sulfate production, as shown in the center of Figure 4.7, the impact of each process is similar to that of nickel sulfate production. The main increase can, again, be seen in the mining and ore processing. Primary extraction still contributes most, but the impact of beneficiation and ore mining increased significantly and appear to be proportional to the carbon intensity of the electricity mix as well. The total impact of the mining and ore processing process is  $4.3 \text{ kgCO}_2\text{eq.}$  in Canada,  $4.2 \text{ kgCO}_2\text{eq.}$  in the Democratic Republic of the Congo (DRC),  $10.2 \text{ kgCO}_2\text{eq.}$  in Russia, and with  $13.7 \text{ kgCO}_2\text{eq.}$  highest in Indonesia. As for nickel sulfate, metal refining has a marginal impact in Norway ( $0.01 \text{ kgCO}_2\text{eq.}$ ), but the impact increases slightly in Finland ( $0.7 \text{ kgCO}_2\text{eq.}$ ) and is with  $2.1 \text{ kgCO}_2\text{eq.}$  highest in China and South Korea. The impact of sulfate production for cobalt sulfate is the highest out of all three battery-grade materials. As previously discussed, the high impact is caused by other energy carriers and only slightly depends on the electricity mix. Norway has the least impact with  $3.3 \text{ kgCO}_2\text{eq.}$ , followed Finland with  $3.5 \text{ kgCO}_2\text{eq.}$ , China with  $4.0 \text{ kgCO}_2\text{eq.}$ , and highest in South Korea with  $4.1 \text{ kgCO}_2\text{eq.}$

In comparison, Congo as a mining country and Norway as a producing country have the lowest impact on GWP as both countries strongly rely on renewable energy sources (International Energy Agency, 2020). Indonesia and South Korea present the country-combination with the highest impacts on GWP. Comparing the obtained results for varying electricity mixes to the literature results of Section 4.2 must be seen critically. The sensitivity analysis on one hand reveals the cruciality of impacts from parameters related to the mining and ore processing, but on the other hand physical parameters such as ore grade and technology is likely to vary within different regions and thus, the resulting impact also varies which explains the deviation of this study in comparison to literature. The GREET model assumes mining in the Democratic Republic of the Congo, while result impact resulting a varying electricity mix in this study is however higher. Opposingly to the case of Finland, where the results by Rinne, Elomaa, and Lundström, 2021 are higher

for both mining and ore processing, and producing in Finland. Comparing the carbon intensity of the Russian and Finnish electricity mixes, the impact of mining and ore processing in Finland would be expected to be lower than that of Russia (International Energy Agency, 2020), i.e. a full production of cobalt sulfate in Finland would yield lower results than the literature reference by Rinne, Elomaa, and Lundström, 2021. Analysing the results clarifies that the electricity mix is a significant indicator, but that other parameters like ore grade and production technology need to be considered for a deeper understanding of locally varying production cases.

### 4.3.3 Manganese Sulfate

The impact profile of manganese sulfate as shown in the right graph of Figure 4.7 remains distinct to that of nickel- and cobalt sulfate. Firstly, the absolute impacts are up to ten times lower, and secondly, the major impact is caused by metal refining. The impact of manganese mining and ore processing for the chosen baseline scenario Gabon-Norway was relatively low ( $0.12 \text{ kgCO}_2\text{eq.}$ ), which in the first place was guessed to be caused by low-carbon electricity mixes of the mining and producing countries. However, this study reveals that the mining and ore processing of manganese is less dependent on the electricity mix as the impact increases only slightly with the higher carbon intensity electricity mixes in Malaysia ( $0.16 \text{ kgCO}_2\text{eq.}$ ), and South Africa ( $0.18 \text{ kgCO}_2\text{eq.}$ ) as mining countries.

The main impact of producing manganese sulfate in Norway traces back to metal refining ( $1.1 \text{ kgCO}_2\text{eq.}$ ). This score increases slightly when producing in France ( $1.2 \text{ kgCO}_2\text{eq.}$ ). For the case of producing in China and Japan (both  $2.0 \text{ kgCO}_2\text{eq.}$ ), the impact of the electricity mixes on metal refining becomes obvious as the impact nearly doubles with carbon-intense electricity mixes of each country (International Energy Agency, 2020). The sulfate production rises proportionally to the carbon intensity of the electricity mix but has a lower contribution on the total impact. The impact of the sulfate production is lowest in Norway ( $0.07 \text{ kgCO}_2\text{eq.}$ ), slightly higher in France ( $0.08 \text{ kgCO}_2\text{eq.}$ ) and highest in Japan and China with  $0.14 \text{ kgCO}_2\text{eq.}$ . In comparison, Gabon as a mining country and Norway as a producing country have the lowest impact on GWP as both countries strongly rely on renewable energy sources. France's electricity mix has a low

impact on GWP which is beneficial for the metal refining process, but as a major fraction of this mix is sourced from nuclear power, the impact on other midpoint categories might increase. The cumulatively highest impact is caused by mining and ore processing in South Africa and producing in Japan, followed right by China as a producing country. The overall impact of mining and ore processing remains little for manganese sulfate production and as the main finding, the carbon intensity of the electricity mix for the producing country is of high relevance.

Compared to the literature-based results in Section 4.2, studies using the global average have a lower impact than the regionalized scenarios modeled in this section. The South African electricity mix is similar to that of China, and the impact of mining and ore processing is furthermore relatively low. Thus, producing manganese sulfate in China can be compared to the literature case of mining and producing in China presented by R. Zhang et al., 2020. The obtained results in this study are significantly lower than these by R. Zhang et al., 2020. As for the ecoinvent 3.7 reference value, all scenarios have a notable higher impact. The results prove the significance of the regional electricity mix. However, the comparison to literature indicates that physical aspects such as the ore grade or production technologies can strongly affect the resulting impact.

## 5 Discussion

The production of batteries for the transportation sector is increasing unprecedently. While carbon emissions in the use phase of battery electric vehicles are successfully reduced, the impact, especially on global warming, is concentrated on the production phase due to electricity- and energy intensive processes. The power- and life cycle characteristics of a battery strongly depend on the implemented cathode. An established and power-determining material contained in cathodes for lithium-ion batteries is NMC, a combination of the battery-grade materials nickel-, cobalt- and manganese sulfate. Dai et al., 2019 conclude that the production of NMC for cathodes is equal to about 15% of the total GWP impact of the whole battery, depending on the exact material composition. To this date, numerous LCA studies were conducted on the assembly and production of batteries. Despite the high contribution of the cathode on the GWP impact of a battery, the value chains of nickel-, cobalt- and manganese sulfate have however not been studied thoroughly.

The three battery-grade materials need to be mined, refined to metal, and further processed to form a metal sulfate. The mining and ore processing process is geographically bound to countries with high ore deposits. Differently, the metal refining and sulfate production processes have no geographic restrictions and thus, the production country can be selected freely. The production process of battery-grade materials is known to be electricity- and energy intensive. Consequently, locating the production of battery-grade materials in a region with low-carbon electricity bears a high potential of reducing environmental impacts of batteries.

China is currently the main producer of batteries and battery-grade materials for the transportation sector. The GWP impact of the production is tremendous as the country's electricity mix consists of nearly 90% fossil fuels (T. Zhang et al., 2021, International Energy Agency, 2020). In contrast, the European Green Deal presented ambitious incentives 'to produce sustainable batteries with the lowest possible environmental impact in Europe' (European Commission, 2020b). To this date, Europe is the second-largest battery producer and consumer of battery-electric vehicles, especially in the Nordic countries. Amongst these is Norway, which is the country with the world's highest number of BEV per capita, sound industrial infrastructure, and most importantly, an electricity mix



that is dominated by renewables (International Energy Agency, 2020). Norway is a potential country to contribute to low-impact batteries by producing low-impact battery-grade materials for the cathode. To bridge the identified research gap, this study focuses on the life cycle impacts related to the value chains of battery-grade materials for cathodes. Two main questions are addressed:

1. What is the environmental impact of battery-grade materials that are refined and produced in Norway?
2. How can regionally varying electricity mixes affect the global warming potential for producing battery-grade materials?

## **5.1 Main Findings**

The environmental impacts of the three NMC battery-grade materials were calculated to assess and benchmark the impact of Norwegian-based value chains, and varying electricity mixes. Hence, process-based life cycle inventories were developed in detail for the production of nickel-, cobalt- and manganese sulfate. The availability of life cycle data and impact scores from industry and literature is found to be generally low in this sequence of the battery value chain. Accessible results vary significantly and thus, evaluating individual differences and assumptions was required to allow comparison. As a general result, the obtained impact scores were benchmarked and indicate good accuracy of the modeled inventories. In conclusion, producing batteries in Norway bears high potential for producing low emission battery-grade materials and consequently lower-impact batteries. However, key-aspects behind this evaluation must be considered and require further discussion. These include the impact of individual processes for producing the three battery-grade materials, as well as the effect of methodological, technical, and regional aspects on the resulting impact.

LCA results for Norwegian-based production were calculated on a process-level for 18 midpoint impact categories for each NMC material. In contrast, manganese sulfate yields almost ten times lower absolute impacts. The impact categories can be divided into two characteristic groups: Ecological or toxicity-related impact categories. Under this consideration, analogies and differences within

the materials can be distinguished. For ecological impact categories, which are the focus of this study, mining and ore processing is the main sources of impact for nickel and cobalt, and metal refining for manganese. For toxicity-related impact categories, the main source is the sulfate production process for all three materials. Utilizing structural path analysis (SPA) shows that the burning of fossil fuels in energy processes and electricity consumption is the main cause of ecological impacts. Thus, the energy-intensive process of producing cobalt sulfate is the dominant contributor for all impact categories and not only toxicity-related categories. SPA furthermore reveals that the toxicity impact of sulfate production is related to ‘water to air’ emissions. Thus, waste and water treatment need further assessment and relevant for future research, especially in the sulfate production.

A point that becomes clear by comparing sulfate production impacts of nickel- and manganese to cobalt sulfate production is the contrast of database and industrial inventories. Ecoinvent assumes stoichiometric conditions for energy consumption and provides direct emissions, while First Cobalt presents primary values for energy consumption but nearly no direct emissions. Thus, there are trade-offs between inventories and none of them provides a fully accurate dataset. However, the results for sulfate production indicate database values potentially underestimate impacts which brings further relevance the aim of this thesis, i.e. to provide industry-based life cycle data for explicit results.

Even though there appears to be a correlation between individual production processes and the affected impact categories, individual processes and stressors that cause the respective impact can vary within the different impact categories. Conducting structural path analyses can provide a deeper understanding regarding the origin of the respective impact. Out of all impact categories, only few if they are commonly analyzed in the field of battery-grade materials. These are global warming (GWP), terrestrial acidification potential (TAP) and particulate matter formation potential (PMFP).

The battery-grade material production is known for high energy and electricity consumption. To analyze the impact from electricity mixes with varying carbon-intensities, and to allow benchmarking to relevant publications, the GWP is chosen as the best suitable impact category and is thus further analyzed in this study.

Valid for all materials, the impact of electricity consumption in Norway is

exceptionally. Studying the production of three battery-grade materials reveals that cobalt and nickel sulfate are of highest- and second-highest priority according to the respective environmental impacts, especially related to the GWP. While the study shows that producing in Norway strongly reduces impacts from refining and sulfate production for both materials, the impact of mining and ore processing remains high and needs to be reduced for further reducing the total impact, especially for nickel- and cobalt sulfate. In comparison to the environmental performance of other mining countries, the presumed mining and ore processing scores significantly lower and thus, the developed value chain for producing nickel- and cobalt sulfate with mining and ore processing in Canada and producing in Norway has the lowest impact relative to other production routes.

The environmental impacts of manganese sulfate are relatively small compared to the above-mentioned impacts from nickel- and cobalt sulfate production. Significant in the manganese value chain is however the dominating use of fossil energy carriers in the metal refining process. Mining in Gabon and producing in Norway reduces the impact significantly due to low-carbon electricity mixes, but the impact could further be reduced by shifting to electricity-based methods in the refining process. Thus, low-emission battery-grade material production requires emission reduction for both, mining and producing country, i.e. production in Norway alone presents only a partial fulfillment of the full reduction potential.

## **5.2 Influencing Parameters**

### **Allocation**

According to the standard for life cycle assessment ISO14044, allocation should be avoided if possible. If required, it should be based on physical factors such as the mass of the output products. In the case of mining and ore processing and refining, allocation of by-product is required since metals are typically found as composites in mines. Thus, in this study, allocation for nickel as a main, and cobalt as by-product is required. Both partitioning cases, mass and economic allocation were analysed initially and compared to pertinent literature. However, the ratio between low ore grade and high market value of cobalt yields more reasonable impacts when economic allocation is used. Besides the downsides of allocation, the principle provided a fundamental life cycle inventory for cobalt

mining and ore processing, and refining which, to the best knowledge, has not been conducted previously. An inventory from the Nickel Institute, in combination with industrial data of Glencore through Norske Utslipp provides detailed data for the mining and ore processing and refining of nickel, with copper and cobalt as by-products. Allocation factors were calculated transparently based on the respective output and average market value of each product. The calculated AFs are presumed to be realistic, as the results of this study are in the same range as literature-reported impacts that do not use allocation.

Some of the evaluated papers consider allocation and report significantly lower impacts than other non-allocation studies. Wei et al., 2020 provides a GWP impact for producing nickel metal based on allocation through system expansion. Thus, negative emissions are allocated to nickel to account for by-products such as cobalt, sulfuric acid, and also heat recovery. Normalizing outputs of different physical units, such as mass and energy in this case. Allocating emissions is objective and not clearly defined which can thus be easily misleading. Consequently, emissions from system expansion and different output units can potentially overly reduce the impact of the main product and yield lower impacts than non-allocation studies. Different allocation methods are bear therefore potential for the slightly higher results obtained in this study.

Meide et al., 2022 provides a study on cobalt metal production and considers economic allocation of nickel as a by-product, analog to this study. The reported GWP impact is however multiple times lower, compared to similar studies that don't use allocation, and also compared to this study. In their publication, Meide et al., 2022 discuss how the impact score is strongly sensitive to varying allocation factors. This study considers a similar ore composition, but lower ore grades than Meide, which is likely to yield distinct allocation factors. Different AFs explain a variation in impacts to some extent, but the gap between the total impacts of both studies is still large. Further comparison is restricted, as the calculation or specific values for Meide's allocation factors are not published.

Allocation is often required in LCA, and can be based on different approaches. The calculation and method for arriving at the respective allocation factors is very objective, yet crucial as it directly determines the impacts of the main product. Thus, allocation is often related to significantly underestimating impacts which must be considered when comparing impacts. This study is based on economic

allocation for producing nickel and cobalt sulfate and yields comparably low results. However, thanks to the detailed results for individual processes, the difference compared to non-allocation studies can be traced back to other factors. These are differences in carbon-intensities of the electricity, varying ore grade or more beneficial production routes that are beneficial in this study and thus, yield lower impacts. Since most impacts are reported as a single-score 'black box', these conclusions are very likely, but cannot be proven definitely.

### **Inventory Quality**

The life cycle inventory is a crucial factor in a LCA and strongly affects reliability, reproducibility, and transparency of the resulting impacts. However, LCAs assess real-life situations and thus, given circumstances often restrict the quality of inventories. This also applies to the field of mining and ore processing, and producing battery-grade materials and hence, also in the context of this study. An ideal inventory in this case should be based on primary industrial data, describing processes-, material-, and energy flows qualitatively and quantitatively, include direct emissions, waste- and water treatment, transportation, and geographic aspects such as the regional electricity mix. However, data scarcity and transparency are a leading problem for the establishment of value chains of battery-grade materials. Reasons are often non-disclosure agreements within the industry and furthermore that the value chain of battery-grade materials presents a niche that only started to get explored in recent years. Additionally, the value chain covers complex and wide-ranging processes like mining and ore processing, metallurgy, and chemical synthesis. Connecting individual processes to a value chain for different materials to perform life cycle is a complex task and, to the best knowledge, has not been assessed previously. Thus, the aim is to provide high-quality inventories while estimating and concluding on required assumptions.

Ecoinvent 3.7 as a major database covers more than 18,000 processes and stressors which makes it an indispensable tool for a broad range of LCAs allowing variance in geographic and technological differences (Wernet et al., 2016). The downside of such a large database however is the limited transparency and in-depth modeling of each process. The GREET model is targeted on, among other fields, the production of batteries (Dai et al., 2019). Except for Nickel sulfate, the value chain of cobalt- and manganese sulfate is available, frequently updated and provided in a more detailed manner than in ecoinvent. One drawback of the GREET model

is that the impact is given as a single-score 'black box' value and thus, disables deeper analysis of the impacts on a process level. To fill this research gap, a process-oriented inventory for nickel-, cobalt-, and manganese sulfate is developed in this study, aiming to maximize the implementation of industry data.

The overall result of this study is that producing battery-grade materials in Norway predicts a slightly higher impact than the 2019 GREET model. Overall, the similarity of results within this study and GREET indicates that this study yields good accuracy. An advantage of the research in this study are the process-oriented, detailed impacts for each material. No information for nickel sulfate is available, and due to single-score impacts in the GREET model, conclusions on differences can only be drawn from the model description. Lower impacts caused by mining and ore processing as a response to higher ore grades and a hydro-based electricity in the DRC explain the difference for cobalt sulfate. The results of this study for producing manganese are likely to be accurate and supported by a revision of the GREET model, stating that the impacts of GREET 2019 likely underestimate the GWP impact of manganese sulfate.

In this study, the processes for nickel- and cobalt mining and ore processing, metal refining for all three materials, and the cobalt sulfate production process were derived from industry data, while processes for manganese mining and ore processing, and nickel- and manganese sulfate production were altered fromecoinvent inventories. The modeled inventories are thus transparent and can be regionalized to regional electricity mixes. Mining and ore processing data derived from the Nickel Institute provides a nearly optimal data set that is implemented in nickel- and cobalt mining and ore processing. Comparing the results of this study to a Nickel Institute study that produces nickel sulfate directly and not via nickel class I shows slightly lower impacts for the direct production (Gediga and Boonzaier, 2021). Yet, producing in Norway via nickel class I yields lower impacts than in other regions. Modeling an inventory for the direct production route in Norway is thus likely to result in a lower impact compared to the production route via nickel class I. The scope of this thesis is to analyse the impact and viability of producing nickel sulfate in Norway in its existing industries. Even though the impact of the value chain created in this study is lower compared to the impacts reported in similar studies, this value chain might not be the most efficient route from an energy- and economic point of view. Thus, further potential impact reductions could be analysed by modeling a direct production route for nickel

sulfate. Based on the Nickel Institute inventory, a detailed inventory for cobalt mining and ore processing could be established through economic allocation of by-products. The available impacts by the Cobalt Institute are only briefly described. The LCA results for cobalt sulfate indicate good accuracy and allow process-oriented analysis.

The derived data for metal refining in Glencore and Eramet obtained through Norske Utslipp provides a high level of detail regarding material output and direct emissions, but to establish a full value chain, process-related data had to be acquired directly through the two companies. Comparing GWP results obtained in this study to literature with similar conditions, indicates good accuracy of the established inventories. Complete comparison on a process-level is not feasible as most literature is only presented in a single-score impact and thus, no quantitative errors can be estimated.

Allowing to regionalize the electricity mix in the inventories enabled comparison to Australian (Norgate, Jahanshahi, and Rankin, 2007, Wei et al., 2020), Chinese (Bai et al., 2022, T. Zhang et al., 2021, R. Zhang et al., 2020, Deng and Gong, 2018), and Finnish literature (Rinne, Elomaa, and Lundström, 2021). For Australia and China, this study yields somewhat higher results than the reported literature, while for Finland it is the opposite. The range of the resulting impact was well-approximated which overall indicates good accuracy of the LCA model, and also the sensitivity mix to the different electricity mix yields close results. As mentioned earlier, especially the mining and ore processing, and also the refining processes are complex and furthermore, environmental parameters vary within regions. Thus, variations in models and results can only be assessed qualitatively. Under these considerations, the established inventories are of high relevance for the established research gap and can contribute strongly to future research with a high level of detail and transparency, good accuracy, and the option to parametrize regional electricity mixes.

### **Database and software**

Another parameter that can yield variations in results is the chosen database and LCA software. Most referred to in literature and industry isecoinvent which is also used in this study, while Norgate, Jahanshahi, and Rankin, 2007 rely on the Australian database Commonwealth Scientific and Industrial Research Organisation (CSIRO). T. Zhang et al., 2021, R. Zhang et al., 2020, and Bai

et al., 2022 refer to the Chinese Process-based Life Cycle Database (CPLCID) as their chosen database. These databases are crucial for conducting life cycle assessment and frequent updates continuously increase the level of accuracy. However, regional, and structural variations between the different databases, and also between internal updates can yield contrasting results. Analog to the database, a change in LCA software can require changes in the inventory modeling and cause varying results in the impact assessment. This study uses the MATLAB-based software Arda, while other studies rely on Simapro (Farjana, Huda, and Mahmud, 2019) or GaBi (Westfall et al., 2016, Rinne, Elomaa, and Lundström, 2021, Gediga and Boonzaier, 2020, Gediga and Boonzaier, 2021).

### **Technological and Environmental Factors**

Each of the life cycle inventories in this study aims to model the production routes based on those of either Glencore or Eramet with according ore material compositions and grades. The typical metal refining production routes can be divided in three major types: Hydrometallurgical, pyrometallurgical or a combination of both. Yet, especially for nickel and cobalt, companies typically develop individual production routes that are optimized for ore specifications and the respective output product (Schmidt, Buchert, and Schebek, 2016). Individual refining processes are thus very complex. To understand and evaluate them in-depth requires specialist background in process engineering and metallurgy. This thesis focuses on the environmental impacts, and while the impacts of the metal refining processes are crucial, in-depth processes the individual processes are beyond the scope of this study.

For refining nickel, literature provides impacts for four hydrometallurgical production routes: Sherritt Gordon and HPAL in Australia by Norgate, Jahanshahi, and Rankin, 2007, leaching and grinding & flotation in China by Bai et al., 2022, and grinding & flotation in China by Deng and Gong, 2018. Comparing the Sherritt Gordon and Leaching process, the direct comparison by Norgate, Jahanshahi, and Rankin, 2007 indicates a lower impact of the Sherritt Gordon refining process compared to leaching. Since both are published within one paper, the aligned methodology allows a qualitative comparison of the two processes as systematic errors are eliminated.

For the following results, the focus is also set on qualitative comparison due to the lack of details. Leaching is implemented for the combined hydro-pyrometallurgical



refining Norway in this study, Australia (Norgate, Jahanshahi, and Rankin, 2007), and hydrometallurgical production routes in China (Bai et al., 2022). Norway has a significantly lower impact, while leaching Australia and China have yields nearly the same impact. Since the process is less energy-intensive, the higher carbon-intensity in Australia does not have a strong effect on the resulting impact and the total score is slightly lower than that of China. Influencing factors are complex, and the only known difference from the Australian to the Chinese production is the utilization of high-pressure acid leaching in Australia which thus appears to cause a lower impact. The results of the two studies just mentioned are the ones closest to the respectiveecoinvent score. Thus, the nickel sulfate production process in ecoinvent is likely to assume refining via leaching in region with a carbon-intensive electricity mix.

Direct comparison of the leaching and grinding & flotation processes of (Bai et al., 2022) suggests a higher impact of the Grinding and Flotation method, which can be also seen in the results by Deng and Gong, 2018. The latter is the only study which provides a process-oriented, detailed GWP impact. Different to this study that has a relatively high contribution from mining and ore processing, and nearly negligible impacts from metal refining, for grinding & flotation, the high impact from refining in addition to the mining and ore processing impacts become clear. The results of this analysis indicate that pyrometallurgical nickel refining appears to have a lower GWP impact than hydrometallurgical refining. Schmidt, Buchert, and Schebek, 2016 and Stanković et al., 2020 summarize the complexity of nickel refining due to numerous ‘mix and match’ parametric options. This clarifies that even though nickel refining has been researched the most compared to cobalt and manganese, the available data leaves open questions and needs further transparency and detail to be able to draw a holistic, quantitative conclusion on the impacts of producing nickel sulfate.

For the refining of cobalt sulfate, process data is available for the GREET model by Dai et al., 2019 and Chordia, Nordelöf, and Ellingsen, 2021 which indicates that both publications assume processes similar to the combined hydro-, pyrometallurgical refining process of this study. The proximity of resulting impacts from Dai et al., 2019 and Chordia, Nordelöf, and Ellingsen, 2021 compared to this study indicate that the modeled cobalt sulfate production process is realistic. The remaining impact scores for cobalt sulfate production are substantially higher. The authors discuss further on the ore grade and composition rather than respective

production routes. Cobalt is typically mined as a by-product due to the low concentration of cobalt in the ore. Thus, the cobalt ore grade can largely increase or reduce efforts in energy and electricity consumption, and hence significantly affect the impacts of mining and ore processing and metal refining.

With the few and largely varying data available for producing cobalt sulfate, the most transparent validation for the results of this study can be achieved from Dai et al., 2019 and Chordia, Nordelöf, and Ellingsen, 2021. Chordia's study is based in Canada and shows slightly higher impacts, which is likely to be caused by the local electricity mix that is more carbon-intensive than the Norwegian one. The results by Rinne, Elomaa, and Lundström, 2021 for Finland and T. Zhang et al., 2021 for China are significantly higher than the previously mentioned studies as the ore grade is low for both, but significantly lower for T. Zhang et al., 2021. This vastly increases the electricity and energy consumption of mining and ore processing and thus explains the high impact. Furthermore, both studies assume a hydrometallurgical production route. Data availability for cobalt refining is scarce, so that the by-production of cobalt and nickel in the refining process is addressed as an approximation. For nickel refining, hydrometallurgical route showed significantly higher impacts which is another explanation for the high impacts reported by Rinne, Elomaa, and Lundström, 2021 and T. Zhang et al., 2021. Due to the complexity of the process, and a general lack of data resolution and transparency for the production of cobalt sulfate, the main conclusion is that particularly for cobalt, resulting impacts are likely to be primarily determined by the ore grade, and secondly by the production process.

The data availability for producing manganese sulfate via ferromanganese or electrolytic manganese was too scarce to draw conclusions regarding production routes.

### **5.3 Limitations**

Much effort has been put into gathering a maximum of industrial data to form detailed and representative life cycle inventories. Life cycle data for battery-grade material value chains is however hardly reported. Two main reasons for the data scarcity are non-disclosure agreements of companies and the fact that only recently, researchers started to also focus on battery-grade materials.

High-quality industrial data was only available for metal refining and thus taken as a foundation for material and process flows of both processes, mining and ore processing and sulfate production. The goal is to provide a value chain that best constitutes production of battery-grade materials in Norway. Thus, industrial data for metal refining is derived from the Norwegian Environment Agency through the data base 'Norske Utslipp'. Detailed energy consumption, direct emissions, waste management and output products are provided for relevant companies Glencore Nikkelverk and Eramet, but no information on the ingoing product consumption or ongoing processes is available.

Initially, waste treatment was included in the LCA. However, no transparent waste treatment methods are provided, and also data regarding waste water treatment is lacking. The impact of waste treatment caused by metal refining was approximated through ecoinvent-based calculations for the two companies and found out to be negligible (<3%). Furthermore, waste and wastewater are only seldomly included in relevant LCAs. The lack of transparency regarding waste treatment would yield inconsistent results. Hence, waste and wastewater are excluded in this study.

Similarly, the resulting impact of transportation is a relevant factor that is included in some LCA studies. The modeled value chains include mining and ore processing, metal refining and sulfate production, and represent a hypothetical scenario of Norwegian-based battery-grade material production. Estimating the mass of materials, transportation modes and distances correctly for such value chains, and especially for mining and ore processing, and the metal refining process is very complex and too wide-ranging for the scope of this thesis.

Nickel and cobalt are typically mined together, and also joined in the metal refining process. Differently for manganese ore and ferromanganese, which are typically the sole valuable output of mining and ore processing and metal refining. Hence, allocation of the impact of by-products is required for the nickel and cobalt value chain. Following the ISO14044 standard, allocation should be avoided since arbitrarily chosen allocation can easily yield misleading results. However, in this study, allocation can be seen as a benefit. Firstly, economic allocation factors are suitable and provide realistic results of metal mining and ore processing and metal refining. Secondly, an inventory for mining and ore processing and refining of cobalt is established which is the first one in this field and contributes to filling the data gap for cobalt-products.

Creating a value chain for mining and ore processing, metal refining and sulfate production is highly complex and depends on numerous parameters such as ore type, technology, company location, process chains etc. Chemical reactions, material flows, and metallurgical processes are thus estimated through a stoichiometric approach in order to adapt to the respective production route. Specifically for sulfate production from pure metals, assumptions were required due to brief description of the process. Processes were chosen to analyse the feasibility of a Norwegian-based value chain, and over-estimate impacts as the worst case.

Further limitations of industrial data for mining and ore processing, and production processes were covered by database values, i.e., ecoinvent 3.7. For manganese mining and ore processing, and nickel- and manganese sulfate production ecoinvent processes were selected as no other inventory data is available. Adapting individual flows of these processes allowed regionalized processes which provided results similar to literature. Comparing ecoinvent impact scores for nickel- and manganese sulfate to respective literature and results of this study, indicates significant variances in both directions. Due to the low level of detail, no right or wrong can be identified. Thus, relying on databases is likely to get a good estimation, but industrial data can provide realistic quantification of impacts. Another limitation to this study is, that commercial chemical compounds are commonly used in the mining and ore processing and refining processes but cannot be modeled through ecoinvent. These additives and thus yield to an underestimation of impacts and provide misleading impressions.

## **5.4 Implications for the Battery Industry**

Freyr and Morrow in Norway, or Northvolt in Sweden – battery production in Northern Europe experiences a rapidly growing market that emphasizes on producing low-emission batteries from a ‘clean’ electricity grid (Freyr, 2022, Morrow, 2022, Northvolt, 2022). The companies are pioneers of the European Green Deal incentives to produce low-impact batteries in Europe (European Commission, 2020b). Aligned with the incentives of the European Green Deal to minimize the impact in all stages of battery production, the research in this study emphasises on reducing the impact of producing battery-grade materials.

Further up the battery value chain, NMC for cathode production yields a significant

GWP impact caused by energy- and electricity intensive processes related to mining and ore processing, and metal refining. Typically, these are purchased from China and the related burden is often excluded for impacts of the battery assembly (Hao et al., 2017). Due to the high impacts related to energy- and electricity consumption which has been revealed in detail in this study, battery-grade materials bear high potential for developing lower-impact batteries when both, mining and production are located in regions with low-carbon electricity mixes (National Minerals Information Center, 2022a, National Minerals Information Center, 2022b, National Minerals Information Center, 2022c).

This study, aligned with pertinent literature, indicates that nickel- and cobalt sulfate production cause about ten times of the impact of producing manganese sulfate. Thus, to reduce the overall impact of a battery, nickel and cobalt production routes should be the highest priority. To produce nickel- and cobalt sulfate, the electricity mix of the mining country has the highest impact reduction potential. The mining and ore processing is obviously bound to regions with high ore deposits, while the producing location of battery-grade materials can be chosen freely. Reducing the carbon impact of both mining and producing is crucial for achieving an overall reduction in environmental impacts. Yet, common mining countries like Australia, Indonesia, Philippines, or Russia rely on fossil fuel-based electricity and thus cause high carbon emissions. Canada, Gabon, or the DRC are further established countries for mining and ore processing nickel, cobalt and manganese that provide renewable-based electricity mixes and hence, reduce carbon emissions in the battery value chain.

This study implies that the metal refining stages for nickel-, cobalt- and manganese metal refining carry high potential to reduce GWP impacts. According to the USGS, industrialized countries such as China, Japan, Korea, and sometimes Germany are selected for producing batteries whilst the GWP impact is immense due to carbon-intensive electricity mixes. France, mostly based on nuclear power, Finland with a growing fraction of renewable energy, and Norway, strongly dominated by renewables present low-carbon alternatives for producing battery-grade material or batteries. The sustainability of nuclear power is strongly debated, but both nuclear energy and renewable sources are considered as the 'greener' choice (Saidi and Omri, 2020).

Batteries can only be considered 'low-emission' if the battery material production

is produced under low-emission conditions, which, in return requires a low-carbon electricity grid for electricity-intensive processes. This study concludes that battery-grade material production in Norway is feasible and predicted to cause lower emissions. Established Norwegian metallurgical companies such as Glencore and Eramet are potential suppliers for nickel, cobalt, and manganese. As indicated previously, there is a strong need to avoid burden shifting in the battery industry and thus, mining and ore processing prior to Norwegian production requires decarbonization.

Finally, there exist further benefits of producing battery-grade materials in Norway beyond the reduced environmental aspects. The world as it is today keeps facing unexpected and dramatic changes. A global pandemic causing standstill in industrial value chains, political threats, and economic dilemmas as a consequence of ongoing wars are frequent news (International Energy Agency, 2022). Thus, battery and especially battery-grade material production in Norway could not only reduce impacts, but also eliminate the risk of interruptions in production and distribution of NMC. Additionally, metal prices for nickel and cobalt have increased exponentially in recent years, and thus create new markets for metal refining in countries like Norway that were not seen as profitable before (*Stock market 2022*).

## **5.5 Recommendations for Future Work**

This study concludes that Norway bears unique potential to contribute to the production of lower-impact batteries due to its low-carbon electricity mix and accessible industrial infrastructure. Establishing coherent value chains of nickel, cobalt and manganese sulfate is highly complex and depends on numerous parameters regarding the processes of mining and ore processing, metal refining and sulfate production and thus, further modeling is required. A relevant finding is that the nickel and cobalt mining and ore processing, and refining processes bear the highest impact reduction potential through low-carbon electricity mixes. Hence, nickel- and cobalt sulfate production should be prioritized over manganese sulfate production for future work. This study provides novel and fundamental conclusions for Norwegian battery-material production. Thus, feasibility is proven, but the level of detail for individual processes and value chains needs more detail

and consider the following aspects:

1. For mining, ore composition, ore grade, the mining type and process flows, as well as the regional electricity mix and energy consumption need further modeling. Under the scope of reducing GWP impacts from mining and ore processing in Canada, Gabon, and the DRC should be further analyzed and considered for the battery production. Sustainability includes both, environmental and social sustainability. Especially in the mining and ore processing sector, safety and health risks of workers must be considered along with the environmental measures under the scope of a 'sustainable battery' (Vingård and Elgstrand, 2013).
2. Evaluating the metal refining process of all three battery-grade materials requires a strong background in metallurgy and process engineering to understand the impacts of individual aspects of hydro- and pyrometallurgical refining. The established inventories highlight the energy- and electricity-intensive processes in metal refining, which thus bear significant GWP reduction potential. Battery-grade materials require high purity and thus, metallurgical processes need to be analyzed under the light of producing for the battery industry in addition to the current production of nickel-, cobalt and manganese for the steel industry. Furthermore, different production routes should be analysed to find the least-impact refining process for battery-grade materials.
3. Developing life cycle inventories for nickel-, cobalt and manganese value chains based on industrial data has revealed the scarcity of accessible data. The value chains were thus completed with regionalized datasets from the ecoinvent database and stoichiometric modeling of the sulfate process. However, results indicate that industry data yields higher impacts than database impacts and thus, the availability of industrial data needs to be increased. Non-disclosure agreements in mining and metallurgical refining present a main restriction. After Glencore Nikkelverk and Eramet Sauda were identified as potential suppliers in Norway, a collaboration for further work bears high potential to conduct high resolution life cycle assessment.

## 6 Conclusion

The GREET model by Dai et al., 2019 is the sole provider of GWP impacts of the three battery-grade materials, nickel-, cobalt- and manganese sulfate production. The GREET model revealed the significant contribution of these materials on the overall GWP impact of the production of a lithium-ion battery. However, the model does not provide process-oriented impacts which would allow the identification of the main contributors. Based on this research gap and motivated through the European Green Deal incentives to produce 'sustainable batteries' in Europe, this study identified the process-based impact of battery-grade materials that are refined and produced in Norway. The GWP impacts, obtained with LCA, were benchmarked to literature and propose that producing battery-grade materials in Norway with local metal refining industry is feasible, and that modeled production routes result in the lowest-calculated impact compared to other countries. The results imply that an electricity mix based on renewable energy sources, such as the Norwegian mix, can largely reduce the impact on climate change. The secondary finding is that both mining and ore processing, and metal refining processes are also electricity intensive. Thus, for providing low-impact battery-grade materials both the mining and producing region require a low-carbon electricity mix. The main implication to the battery industry is therefore that producing batteries in Norway has large emission reduction potential, but to reach the full potential, the mining and ore processing process must be de-carbonised as well.

Quantitative life cycle assessment on the impact of producing battery-grade materials in Norway requires a detailed and accurate life cycle inventory. Thus, a full set of process-oriented life cycle inventories for nickel-, cobalt- and manganese sulfate production was established. The focus of the modeled value chain lies on implementing industry data to the most possible extent, and to provide transparent inventories that connects the processes mining and ore processing, metal refining and sulfate production. The established inventories allow to regionalize processes, so that the impact response to a change in carbon intensity of regional electricity mixes can be analysed. Each process step of the value chain requires expertise in metallurgy, chemical-, and process engineering. This study focuses on the environmental impacts of battery-grade materials and due to scarcity of industrial data and literature, carefully considered assumptions had to be taken for establishing life cycle inventories. The LCA impacts for producing in



Norway, as well as the sensitivity to varying electricity mixes were benchmarked against relevant literature. Each of the three battery-grade materials was validated to yield realistic results with good accuracy and thus suggests that assumptions in the inventory are chosen correctly. The total production of nickel- and cobalt sulfate causes about ten times of the impact of producing manganese. Thus, the highest emission reduction potential lies in the value chains of nickel- and cobalt sulfate which should therefore be prioritized in future research and implemented in industrial settings. The impact reduction related to the Norwegian electricity mix was expected, while the detailedness of the life cycle inventories revealed the significance of the electricity mix in the mining country.

Based on these conclusions, the case of Norwegian-based battery-grade material production bears high potential to contribute to a low-emission battery production. For further development of the established value chain, the individual metallurgic and chemical processes of particularly nickel- and cobalt sulfate should be further discussed. To overcome data scarcity, the focus should be furthermore set towards establishing transparent and detailed industrial data. In the value chain of battery-grade materials, not only the production phase in Norway, but also mining and ore processing requires low-emission status and requires deeper assessment that includes local ore- and mining related parameters, in addition to the regional electricity mix. These assessments are crucial for providing further identifying and quantifying environmental burdens. This thesis established fundamental framework behind the concept, but based on conclusions of future work, precise policy implications can contribute to the realization of the low-emission batteries as part of the European Green Deal.

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# Appendix A - Inventory Modeling

## A.1 Allocation Factors

Table A.1: Commodity prices for nickel and cobalt co-production.

| <b>Material</b> | <b>Price in \$/kg</b> | <b>Time span</b> | <b>Reference</b>                    |
|-----------------|-----------------------|------------------|-------------------------------------|
| Nickel          | 15.37                 | 2012-2022        | <i>Stock market 2022</i>            |
| Cobalt          | 42.18                 | 2012-2022        | <i>Stock market 2022</i>            |
| Copper          | 6.67                  | 2012-2018        | <i>Metalary Metal Prices 2022</i>   |
| Sulfuric Acid   | 0.14                  | 2019             | <i>US Producer Price Index 2019</i> |

Table A.2: Economic allocation factors for mining and ore processing, and refining of nickel and cobalt.

| <b>Material</b> | <b>Allocation factor: Mining<br/>and Ore Processing</b> | <b>Allocation factor:<br/>Metal refining process</b> |
|-----------------|---|--|
| Nickel          | 82 %  | 81 %   |
| Cobalt          | 10 %  | 9 %  |
| Copper          | 8 %   | 9 %  |
| Sulfuric Acid   | -   | 1 %  |

## A.2 Nickel Sulfate

Table A.3: Life Cycle Inventory Nickel Sulfate

| <b>Sulfate production</b>                   |       |               |                 |
|---|-------|---------------|-----------------|
| <b>Input</b>                                |       |               |                 |
| Nickel class I                              | kg    | 4.00E-01      |                 |
| Chemical factory, organics                  | p     | 4.00E-10      |                 |
| Nitrogen, liquid                            | kg    | 1.90E-02      |                 |
| Sulfuric acid                               | kg    | 6.67E-01      |                 |
| Tap water                                   | kg    | 2.60E-02      |                 |
| Water                                       | $m^3$ | 1.81E-02      |                 |
| <b>Output</b>                               |       |               |                 |
| Nickel sulfate                              | kg    | 1.00E+00      |                 |
| <b>Energy consumption</b>                   |       |               |                 |
| Electricity, medium voltage                 | kWh   | 4.16E-01      |                 |
| Natural gas                                 | MJ    | 2.15E+00      |                 |
| Heat, from steam, in chemical industry      | MJ    | 2.00E-01      |                 |
| <b>Direct emissions</b>                     |       | <b>to air</b> | <b>to water</b> |
| Nickel, ion                                 | kg    |               | 2.10E-03        |
| Nitrogen                                    | kg    | 1.90E-02      |                 |
| Sulfur                                      | kg    |               | 1.15E-03        |
| Water                                       | $m^3$ | 1.40E-03      | 1.67E-02        |
| <b>Metal refining (economic allocation)</b> |       |               |                 |
| <b>Input</b>                                |       |               |                 |
| Nickel matte                                | kg    | 7.89E-01      |                 |
| <b>Output</b>                               |       |               |                 |
| Nickel class I                              | kg    | 4.00E-01      |                 |
| <b>Energy consumption</b>                   |       |               |                 |
| Electricity                                 | kWh   | 2.08E+00      |                 |

|         |    |          |
|---------|----|----------|
| Coke    | MJ | 1.71E-03 |
| LFO     | MJ | 3.90E-02 |
| Propane | MJ | 1.29E-02 |

| <b>Direct emissions</b>           |    | <b>to air</b> | <b>to water</b> |
|-----------------------------------|----|---------------|-----------------|
| Ammonia                           | kg | 9.30E-06      |                 |
| Arsen                             | kg |               | 1.27E-06        |
| Carbon dioxide fossil             | kg | 5.87E-02      |                 |
| Chlorinated alkylbenzenes         | kg |               | 3.00E-08        |
| Chlorine gas                      | kg | 5.17E-06      |                 |
| Copper                            | kg | 3.34E-06      | 1.91E-06        |
| Dioxins in toxic equivalents      | kg |               | 1.12E-13        |
| Hydrochloric acid                 | kg | 1.50E-06      |                 |
| Iron                              | kg |               | 6.74E-06        |
| Nickel                            | kg | 2.91E-06      | 3.69E-06        |
| Nitrous oxide (N2O)               | kg | 4.94E-05      |                 |
| Organic solvents                  | kg | 1.68E-04      |                 |
| Particulate matter (PM2.5 - PM10) | kg | 3.49E-06      |                 |
| Sulfate                           | kg |               | 6.37E-02        |
| Sulfur dioxide                    | kg | 6.78E-05      |                 |
| Sulfur trioxide                   | kg | 3.75E-08      |                 |
| Zinc                              | kg |               | 3.82E-07        |

### **Primary extraction**

#### **Input**

|                          |    |          |
|--------------------------|----|----------|
| Ore concentrate          | kg | 1.34E+01 |
| Ammonia                  | kg | 4.58E-04 |
| Coal                     | kg | 6.22E-02 |
| Collector                | kg | 3.17E-04 |
| Diesel                   | kg | 4.58E-03 |
| Electrodes               | kg | 4.91E-03 |
| External concentrate     | kg | 1.70E-01 |
| Ferric chloride          | kg | 2.13E-04 |
| Gasoline                 | kg | 6.22E-04 |
| Graphite                 | kg | 2.45E-04 |
| Ground water             | kg | 3.60E+00 |
| Hydrochloric acid (100%) | kg | 7.53E-05 |

|                          |    |          |
|--------------------------|----|----------|
| Hydrogen peroxide (100%) | kg | 1.44E-03 |
| Hydrogen sulphide        | kg | 1.80E-02 |
| Internal recovery        | kg | 2.36E-01 |
| Iron scrap               | kg | 2.36E-03 |
| Lake water               | kg | 6.55E-01 |
| Lime                     | kg | 5.24E-02 |
| Limestone                | kg | 7.20E-01 |
| Lubricant                | kg | 2.32E-04 |
| Natural gas              | kg | 4.25E-02 |
| Nitric acid              | kg | 3.60E-07 |
| Nitrogen liquid          | kg | 2.39E-04 |
| Oxygen gaseous           | kg | 1.28E+00 |
| Pellet feed              | kg | 3.11E-02 |
| Petrol coke              | kg | 1.57E-02 |
| Process water            | kg | 3.21E+00 |
| Propane                  | kg | 5.56E-06 |
| Rain water               | kg | 2.62E-02 |
| River water              | kg | 1.05E+01 |
| Silica                   | kg | 1.01E+00 |
| Slag (containing Ni)     | kg | 1.57E-01 |
| Soda                     | kg | 1.51E-03 |
| Sodium hydroxide (100%)  | kg | 2.75E-03 |
| Steam                    | kg | 1.05E+00 |
| Sulphur                  | kg | 2.52E-01 |
| Sulphuric acid           | kg | 5.24E-01 |
| Water                    | kg | 1.57E+00 |

### **Output**

|                                 |    |          |
|---------------------------------|----|----------|
| Nickel matte (contains Co & Cu) | kg | 7.89E-01 |
|---------------------------------|----|----------|

### **Energy consumption**

|                |     |          |
|----------------|-----|----------|
| Electricity    | kWh | 2.18E+00 |
| Heavy fuel oil | MJ  | 1.54E+00 |
| LFO            | MJ  | 3.21E-02 |
| LPG            | MJ  | 2.06E-01 |
| Natural gas    | MJ  | 8.18E+00 |

| <b>Direct emissions</b> |    | <b>to air</b> | <b>to water</b> |
|-------------------------|----|---------------|-----------------|
| Antimony                | kg | 2.09E-09      |                 |
| Arsenic                 | kg | 1.08E-05      |                 |
| Cadmium                 | kg | 3.27E-06      |                 |
| Carbon dioxide          | kg | 8.84E-01      |                 |
| Carbon monoxide         | kg | 2.52E-03      |                 |
| Chromium                | kg | 1.64E-06      |                 |
| Cobalt                  | kg | 1.18E-05      |                 |
| Copper                  | kg | 1.34E-04      |                 |
| Dust (PM10)             | kg | 7.20E-03      |                 |
| Dust (PM2.5-PM10)       | kg | 4.91E-03      |                 |
| Dust(PM>10)             | kg | 8.18E-05      |                 |
| Hydrochloric acid       | kg | 5.24E-05      |                 |
| Lead                    | kg | 9.16E-05      |                 |
| Manganese               | kg | 6.87E-06      |                 |
| Mercury                 | kg | 4.25E-07      |                 |
| Methane                 | kg | 3.11E-05      |                 |
| Nickel                  | kg | 2.45E-04      |                 |
| Nitrogen dioxide        | kg | 2.36E-04      |                 |
| Nitrogen oxides         | kg | 1.28E-03      |                 |
| NMVOC (unspecified)     | kg | 3.01E-05      |                 |
| Sulphur                 | kg | 1.15E+00      |                 |
| Sulphur dioxide         | kg | 1.21E-05      |                 |
| Sulphuric acid          | kg | 7.53E-03      |                 |
| Water vapour            | kg | 1.05E+00      |                 |
| Zinc                    | kg | 2.49E-05      |                 |

### **Beneficiation**

---

#### **Input**

|                                  |    |          |  |
|----------------------------------|----|----------|--|
| Mined ore                        | kg | 3.64E+01 |  |
| Activator (neglected)            | kg | 1.44E-04 |  |
| Antiscalant (neglected)          | kg | 5.24E-06 |  |
| Collector (neglected)            | kg | 7.53E-03 |  |
| Depressant (neglected)           | kg | 3.60E-03 |  |
| Diesel                           | kg | 1.54E-02 |  |
| External concentrate (neglected) | kg | 1.24E-02 |  |
| Ferrous sulphate                 | kg | 1.44E-06 |  |

|                                |    |          |
|--------------------------------|----|----------|
| Flocculant (neglected)         | kg | 1.77E-02 |
| Frother (neglected)            | kg | 1.67E-03 |
| Gasoline                       | kg | 3.60E-05 |
| Grinding media (neglected)     | kg | 3.60E-02 |
| Internal recovery              | kg | 6.55E-03 |
| Internal recovery (Ni content) | kg | 2.26E-01 |
| Lime                           | kg | 2.03E-02 |
| Lubricant                      | kg | 7.85E-04 |
| Nickel intermediate            | kg | 1.54E-03 |
| Nitric acid                    | kg | 5.24E-05 |
| Phosphates                     | kg | 9.49E-05 |
| Resins                         | kg | 8.18E-06 |
| Soda                           | kg | 8.84E-03 |
| Sodium bisulphite              | kg | 1.70E-02 |
| Sodium cyanide                 | kg | 3.60E-05 |
| Sulphuric acid                 | kg | 6.22E-04 |

### **Output**

|                 |    |          |
|-----------------|----|----------|
| Ore concentrate | kg | 1.34E+01 |
|-----------------|----|----------|

### **Energy consumption**

|                |     |          |
|----------------|-----|----------|
| Electricity    | kWh | 2.27E+00 |
| Hard coal      | MJ  | 1.11E+00 |
| Heavy fuel oil | MJ  | 1.67E-01 |
| LPG            | MJ  | 6.87E-05 |
| Natural gas    | MJ  | 1.87E+00 |

### **Direct emissions**

|                     |    |          |
|---------------------|----|----------|
| Carbon dioxide      | kg | 1.64E-01 |
| Carbon monoxide     | kg | 3.60E-05 |
| Dust (PM10)         | kg | 4.91E-05 |
| Dust (PM2.5-PM10)   | kg | 9.16E-06 |
| Dust (unspecified)  | kg | 4.91E-04 |
| Methane             | kg | 1.15E-05 |
| Nitrogen oxides     | kg | 2.23E-04 |
| NMVOC (unspecified) | kg | 9.82E-06 |
| Sulphur dioxide     | kg | 1.87E-04 |

**to air**

**to water**

|              |    |          |
|--------------|----|----------|
| Water vapour | kg | 2.36E-03 |
|--------------|----|----------|

**Ore mining**

---

**Input**

|              |    |          |
|--------------|----|----------|
| Ni-Co-Cu ore | kg | 6.23E+01 |
| Lubricant    | kg | 1.24E-02 |
| Other ore    | kg | 8.52E-05 |

**Output**

|           |    |          |
|-----------|----|----------|
| Mined ore | kg | 3.64E+01 |
|-----------|----|----------|

**Energy consumption**

|             |     |          |
|-------------|-----|----------|
| Electricity | kWh | 1.45E+00 |
| LPG         | MJ  | 2.32E-04 |

**Direct emissions**

|                     |    | <b>to air</b> | <b>to water</b> |
|---------------------|----|---------------|-----------------|
| Carbon dioxide      | kg | 1.93E-01      |                 |
| Carbon monoxide     | kg | 3.93E-04      |                 |
| Dust (PM10)         | kg | 1.37E-04      |                 |
| Dust (PM2.5-PM10)   | kg | 1.41E-05      |                 |
| Dust (unspecified)  | kg | 2.55E-04      |                 |
| Methane             | kg | 3.27E-04      |                 |
| Nitrogen dioxide    | kg | 1.93E-04      |                 |
| Nitrogen oxides     | kg | 3.93E-04      |                 |
| NMVOC (unspecified) | kg | 1.34E-05      |                 |
| Sulphur dioxide     | kg | 1.77E-04      |                 |

## A.3 Cobalt Sulfate

Table A.4: Life Cycle Inventory Cobalt Sulfate

### Sulfate production

#### Input

|                         |    |          |
|-------------------------|----|----------|
| Cobalt Class I (99.98%) | kg | 2.12E-01 |
| Water                   | kg | 3.38E+00 |
| Calcium Carbonate       | kg | 1.40E-01 |
| Cyanex 272 (neglected)  | kg | 6.00E-04 |
| D2EHPA (neglected)      | kg | 1.00E-04 |
| Flocculant (neglected)  | kg | 5.00E-05 |
| Quicklime               | kg | 1.40E-01 |
| Sodium Hydroxide (50%)  | kg | 8.80E-01 |
| Sulphuric Acid (93%)    | kg | 1.15E+00 |
| Water                   | kg | 1.00E-03 |

#### Output

|                |    |          |
|----------------|----|----------|
| Cobalt sulfate | kg | 1.00E+00 |
|----------------|----|----------|

#### Energy consumption

|             |     |          |
|-------------|-----|----------|
| Electricity | kWh | 1.16E+00 |
| Diesel      | kg  | 4.00E-03 |
| Natural Gas | MJ  | 3.00E+00 |

#### Direct emissions

|                       |    |               |                 |
|-----------------------|----|---------------|-----------------|
|                       |    | <b>to air</b> | <b>to water</b> |
| Carbon dioxide fossil | kg | 1.00E-01      |                 |

### Metal refining (economic allocation)

#### Input

|              |    |      |
|--------------|----|------|
| Nickel matte | kg | 1.14 |
|--------------|----|------|

#### Output

|                |    |      |
|----------------|----|------|
| Cobalt class I | kg | 0.21 |
|----------------|----|------|



**Energy consumption**

|             |     |          |
|-------------|-----|----------|
| Electricity | kWh | 3.00E+00 |
| Coke        | MJ  | 2.46E-03 |
| LFO         | MJ  | 5.61E-02 |
| Propane     | MJ  | 1.85E-02 |

**Direct emissions**

|                                   |    | <b>to air</b> | <b>to water</b> |
|-----------------------------------|----|---------------|-----------------|
| Ammonia                           | kg | 1.34E-05      |                 |
| Arsen                             | kg |               | 1.83E-06        |
| Carbon dioxide fossil             | kg | 8.46E-02      |                 |
| Chlorinated alkylbenzenes         | kg |               | 4.32E-08        |
| Chlorine gas                      | kg | 7.45E-06      |                 |
| Copper                            | kg | 4.81E-06      | 2.75E-06        |
| Dioxins in toxic equivalents      | kg |               | 1.62E-13        |
| Hydrochloric acid                 | kg | 2.16E-06      |                 |
| Iron                              | kg |               | 9.71E-06        |
| Nickel                            | kg | 4.19E-06      | 5.31E-06        |
| Nitrous oxide (N2O)               | kg | 7.12E-05      |                 |
| Organic solvents                  | kg | 2.43E-04      |                 |
| Particulate matter (PM2.5 - PM10) | kg | 5.02E-06      |                 |
| Sulfate                           | kg |               | 9.18E-02        |
| Sulfur dioxide                    | kg | 9.78E-05      |                 |
| Sulfur trioxide                   | kg | 5.40E-08      |                 |
| Zinc                              | kg |               | 5.51E-07        |

**Primary extraction****Input**

---

|                      |    |          |
|----------------------|----|----------|
| Ore concentrate      | kg | 1.93E+01 |
| Ammonia              | kg | 6.60E-04 |
| Coal                 | kg | 8.96E-02 |
| Coke                 | kg | 7.54E-02 |
| Collector            | kg | 4.57E-04 |
| Diesel               | kg | 6.60E-03 |
| Electrodes           | kg | 7.07E-03 |
| External concentrate | kg | 2.45E-01 |
| Ferric chloride      | kg | 3.07E-04 |
| Gasoline             | kg | 8.96E-04 |

|                          |    |          |
|--------------------------|----|----------|
| Graphite                 | kg | 3.54E-04 |
| Ground water             | kg | 5.19E+00 |
| Hydrochloric acid (100%) | kg | 1.08E-04 |
| Hydrogen peroxide (100%) | kg | 2.07E-03 |
| Hydrogen sulphide        | kg | 2.59E-02 |
| Internal recovery        | kg | 3.40E-01 |
| Iron scrap               | kg | 3.40E-03 |
| Lake water               | kg | 9.43E-01 |
| Lime                     | kg | 7.54E-02 |
| Limestone                | kg | 1.04E+00 |
| Lubricant                | kg | 3.35E-04 |
| Natural gas              | kg | 6.13E-02 |
| Nitric acid              | kg | 5.19E-07 |
| Nitrogen liquid          | kg | 3.44E-04 |
| Oxygen gaseous           | kg | 1.84E+00 |
| Pellet feed              | kg | 4.48E-02 |
| Petrol coke              | kg | 2.26E-02 |
| Process water            | kg | 4.62E+00 |
| Propane                  | kg | 8.02E-06 |
| Rain water               | kg | 3.77E-02 |
| River water              | kg | 1.51E+01 |
| Silica                   | kg | 1.46E+00 |
| Slag (containing Ni)     | kg | 2.26E-01 |
| Soda                     | kg | 2.17E-03 |
| Sodium hydroxide (100%)  | kg | 3.96E-03 |
| Steam                    | kg | 1.51E+00 |
| Sulphur                  | kg | 3.63E-01 |
| Sulphuric acid           | kg | 7.54E-01 |
| Water                    | kg | 2.26E+00 |

### **Output**

|                                 |    |          |
|---------------------------------|----|----------|
| Nickel matte (contains Co & Cu) | kg | 1.14E+00 |
|---------------------------------|----|----------|

### **Energy consumption**

|                |     |          |
|----------------|-----|----------|
| Electricity    | kWh | 3.14E+00 |
| Heavy fuel oil | MJ  | 2.22E+00 |
| LFO            | MJ  | 4.62E-02 |

|             |    |          |
|-------------|----|----------|
| LPG         | MJ | 2.97E-01 |
| Natural gas | MJ | 1.18E+01 |

| <b>Direct emissions</b> |    | <b>to air</b> | <b>to water</b> |
|-------------------------|----|---------------|-----------------|
| Antimony                | kg | 3.02E-09      |                 |
| Arsenic                 | kg | 1.56E-05      |                 |
| Cadmium                 | kg | 4.72E-06      |                 |
| Carbon dioxide          | kg | 1.27E+00      |                 |
| Carbon monoxide         | kg | 3.63E-03      |                 |
| Chromium                | kg | 2.36E-06      |                 |
| Cobalt                  | kg | 1.70E-05      |                 |
| Copper                  | kg | 1.93E-04      |                 |
| Dust (PM10)             | kg | 1.04E-02      |                 |
| Dust (PM2.5-PM10)       | kg | 7.07E-03      |                 |
| Dust(PM>10)             | kg | 1.18E-04      |                 |
| Hydrochloric acid       | kg | 7.54E-05      |                 |
| Lead                    | kg | 1.32E-04      |                 |
| Manganese               | kg | 9.90E-06      |                 |
| Mercury                 | kg | 6.13E-07      |                 |
| Methane                 | kg | 4.48E-05      |                 |
| Nickel                  | kg | 3.54E-04      |                 |
| Nitrogen dioxide        | kg | 3.40E-04      |                 |
| Nitrogen oxides         | kg | 1.84E-03      |                 |
| NMVOC (unspecified)     | kg | 4.34E-05      |                 |
| Sulphur                 | kg | 1.74E-05      |                 |
| Sulphur dioxide         | kg | 1.65E+00      |                 |
| Sulphuric acid          | kg | 1.08E-02      |                 |
| Water vapour            | kg | 1.51E+00      |                 |
| Zinc                    | kg | 3.58E-05      |                 |

### **Beneficiation**

#### **Input**

|                         |    |          |
|-------------------------|----|----------|
| Mined ore               | kg | 5.38E+01 |
| Activator (neglected)   | kg | 2.07E-04 |
| Antiscalant (neglected) | kg | 7.54E-06 |
| Collector (neglected)   | kg | 1.08E-02 |
| Depressant (neglected)  | kg | 5.19E-03 |

|                                  |    |          |
|----------------------------------|----|----------|
| Diesel                           | kg | 2.22E-02 |
| External concentrate (neglected) | kg | 1.79E-02 |
| Ferrous sulphate                 | kg | 2.07E-06 |
| Flocculant (neglected)           | kg | 2.55E-02 |
| Frother (neglected)              | kg | 2.40E-03 |
| Gasoline                         | kg | 5.19E-05 |
| Grinding media (neglected)       | kg | 5.19E-02 |
| Internal recovery (neglected)    | kg | 9.43E-03 |
| Lime                             | kg | 2.92E-02 |
| Lubricant                        | kg | 1.13E-03 |
| Nickel intermediate              | kg | 2.22E-03 |
| Nitric acid                      | kg | 7.54E-05 |
| Phosphates                       | kg | 1.37E-04 |
| Resins                           | kg | 1.18E-05 |
| Soda                             | kg | 1.27E-02 |
| Sodium bisulphite                | kg | 2.45E-02 |
| Sodium cyanide                   | kg | 5.19E-05 |
| Sulphuric acid                   | kg | 8.96E-04 |

### **Output**

|                 |    |          |
|-----------------|----|----------|
| Ore concentrate | kg | 1.93E+01 |
|-----------------|----|----------|

### **Energy consumption**

|                |     |          |
|----------------|-----|----------|
| Electricity    | kWh | 3.27E+00 |
| Hard coal      | MJ  | 1.60E+00 |
| Heavy fuel oil | MJ  | 2.40E-01 |
| LPG            | MJ  | 9.90E-05 |
| Natural gas    | MJ  | 2.69E+00 |

### **Direct emissions**

|                    |    | <b>to air</b> | <b>to water</b> |
|--------------------|----|---------------|-----------------|
| Carbon dioxide     | kg | 2.36E-01      |                 |
| Carbon monoxide    | kg | 5.19E-05      |                 |
| Dust (PM10)        | kg | 7.07E-05      |                 |
| Dust (PM2.5-PM10)  | kg | 1.32E-05      |                 |
| Dust (unspecified) | kg | 7.07E-04      |                 |
| Methane            | kg | 1.65E-05      |                 |
| Nitrogen oxides    | kg | 3.21E-04      |                 |

|                     |    |          |
|---------------------|----|----------|
| NMVOC (unspecified) | kg | 1.41E-05 |
| Sulphur dioxide     | kg | 2.69E-04 |
| Water vapour        | kg | 3.40E-03 |

### **Ore mining**

---

#### **Input**

|              |    |          |
|--------------|----|----------|
| Ni-Co-Cu ore | kg | 8.98E+01 |
| Lubricant    | kg | 1.79E-02 |
| Other ore    | kg | 1.23E-04 |

#### **Output**

|           |    |          |
|-----------|----|----------|
| Mined ore | kg | 5.38E+01 |
|-----------|----|----------|

#### **Energy consumption**

|             |     |          |
|-------------|-----|----------|
| Electricity | kWh | 2.10E+00 |
| LPG         | MJ  | 3.35E-04 |

#### **Direct emissions**

|                     |    | <b>to air</b> | <b>to water</b> |
|---------------------|----|---------------|-----------------|
| Carbon dioxide      | kg | 2.78E-01      |                 |
| Carbon monoxide     | kg | 5.66E-04      |                 |
| Dust (PM10)         | kg | 1.98E-04      |                 |
| Dust (unspecified)  | kg | 3.68E-04      |                 |
| Methane             | kg | 4.72E-04      |                 |
| Nitrogen dioxide    | kg | 2.78E-04      |                 |
| Nitrogen oxides     | kg | 5.66E-04      |                 |
| NMVOC (unspecified) | kg | 1.93E-05      |                 |
| Sulphur dioxide     | kg | 2.55E-04      |                 |

## A.4 Manganese Sulfate

Table A.5: Life cycle Inventory Manganese Sulfate

| <b>Sulfate production</b>              |       |               |                 |
|--|-------|---------------|-----------------|
| <b>Input</b>                           |       |               |                 |
| Ferromanganese                         | kg    | 3.60E-01      |                 |
| Tap water                              | kg    | 6.11E-03      |                 |
| Sulfuric acid                          | kg    | 2.79E-01      |                 |
| Chemical factory, organics             | p     | 9.40E-11      |                 |
| Water (Cooling, well in ground, river) | $m^3$ | 4.25E-03      |                 |
| <b>Output</b>                          |       |               |                 |
| Manganese sulfate                      | kg    | 1.00E+00      |                 |
| <b>Energy consumption</b>              |       |               |                 |
| Natural gas                            | MJ    | 5.05E-01      |                 |
| Electricity, medium voltage            | kWh   | 9.78E-02      |                 |
| Heat, from steam, in chemical industry | MJ    | 4.70E-02      |                 |
| <b>Direct emissions</b>                |       |               |                 |
|  |       | <b>to air</b> | <b>to water</b> |
| Water                                  | $m^3$ | 3.29E-04      | 3.97E-03        |
| Manganese                              | kg    | 3.13E-04      | 7.92E-04        |
| Sulfuric acid                          | kg    | 5.58E-04      |                 |
| Sulfur                                 | kg    |               | 5.05E-04        |
| <b>Metal refining</b>                  |       |               |                 |
| <b>Input</b>                           |       |               |                 |
| Processed Mn ore                       | kg    | 3.80E-01      |                 |
| <b>Output</b>                          |       |               |                 |
| Ferromanganese                         | kg    | 3.60E-01      |                 |
| <b>Energy consumption</b>              |       |               |                 |
| Electricity                            | kWh   | 1.37E+00      |                 |
| Coal anthracite                        | MJ    | 1.62E+00      |                 |

|                                   |    |               |                 |
|-----------------------------------|----|---------------|-----------------|
| Coke                              | MJ | 4.87E+00      |                 |
| Propane                           | MJ | 1.01E-02      |                 |
| <b>Direct emissions</b>           |    | <b>to air</b> | <b>to water</b> |
| Other inorganic compounds         | kg | 4.11E-07      |                 |
| Arsen                             | kg |               | 3.76E-08        |
| Benzo[a]pyren                     | kg | 3.92E-10      | 2.46E-11        |
| Benzo[g,h,i]perylen               | kg | 4.32E-10      | 2.16E-11        |
| Lead                              | kg | 2.44E-08      | 1.40E-08        |
| Cyanid total                      | kg |               | 3.21E-06        |
| Cadmium                           | kg |               | 8.64E-10        |
| Carbon dioxide fossil             | kg | 6.51E-01      |                 |
| Copper                            | kg | 3.84E-07      | 3.25E-07        |
| Chromium                          | kg | 3.54E-08      | 2.25E-08        |
| Mercury                           | kg | 5.84E-09      | 1.08E-10        |
| Nickel                            | kg | 2.16E-08      | 1.27E-07        |
| Nitrous oxide                     | kg | 1.08E-05      |                 |
| Manganese                         | kg | 1.97E-06      | 1.37E-05        |
| Molybdenum                        | kg | 2.44E-08      | 3.00E-07        |
| Naftalen                          | kg | 3.70E-08      | 2.16E-11        |
| Nitrogen total                    | kg |               | 3.08E-05        |
| Nitrogenoxides                    | kg | 8.27E-05      |                 |
| PAH Total                         | kg | 9.07E-08      | 3.44E-09        |
| Particulate matter (PM2.5 - PM10) | kg | 6.46E-05      |                 |
| Zinc                              | kg | 3.71E-07      | 5.77E-07        |
| Sulfur dioxide                    | kg | 5.25E-05      |                 |
| Total organic carbon              | kg |               | 2.07E-05        |
| Dry matter suspended              | kg |               | 4.83E-05        |

### Ore Mining

#### Input

|   |    |          |
|---|----|----------|
| Manganese ore                                       | kg | NA       |
| Aluminium hydroxide factory                         | p  | 4.45E-12 |
| Blasting  | kg | 1.39E-04 |
| Conveyor belt                                       | m  | 3.99E-08 |
| Mine infrastructure, open cast, non-ferrous metal   | p  | 5.97E-12 |
| Mine infrastructure, underground, non-ferrous metal | p  | 2.56E-12 |

|  |    |          |
|--|----|----------|
| Steel, chromium steel 18/8, hot rolled | kg | 1.59E-04 |
|--|----|----------|

**Output**

|                  |    |          |
|------------------|----|----------|
| Processed Mn ore | kg | 3.80E-01 |
|------------------|----|----------|

**Energy consumption**

|                             |     |          |
|-----------------------------|-----|----------|
| Electricity, medium voltage | kWh | 8.63E-02 |
|-----------------------------|-----|----------|

|                                    |    |          |
|------------------------------------|----|----------|
| Diesel, burned in building machine | MJ | 9.31E-01 |
|------------------------------------|----|----------|

**Direct emissions**

|                                    |                | <b>to air</b> | <b>to water</b> |
|------------------------------------|----------------|---------------|-----------------|
| Aluminium                          | kg             | 1.22E-09      |                 |
| Arsenic, ion                       | kg             |               | 3.48E-11        |
| BOD5, Biological Oxygen Demand     | kg             |               | 3.48E-08        |
| Chromium                           | kg             | 7.79E-11      |                 |
| COD, Chemical Oxygen Demand        | kg             |               | 5.24E-06        |
| Copper, ion                        | kg             |               | 3.48E-11        |
| Dissolved solids                   | kg             |               | 1.74E-08        |
| DOC, Dissolved Organic Carbon      | kg             |               | 2.05E-08        |
| Iron                               | kg             | 1.81E-06      |                 |
| Iron, ion                          | kg             |               | 1.22E-09        |
| Lead                               | kg             |               | 3.48E-11        |
| Magnesium                          | kg             |               | 4.75E-10        |
| Particulates, < 2.5 um             | kg             | 3.64E-09      |                 |
| Particulates, > 10 um              | kg             | 3.76E-08      |                 |
| Particulates, < 2.5 um, and < 10um | kg             | 3.27E-08      |                 |
| Silicon                            | kg             |               | 3.18E-08        |
| TOC, Total Organic Carbon          | kg             |               | 2.05E-08        |
| Water, river                       | m <sup>3</sup> |               | 4.29E-04        |
| Zinc, ion                          | kg             |               | 3.48E-11        |

**Direct emissions (not specified)**

|  |                | <b>N/S</b> |
|--|----------------|------------|
| Occupation, mineral extraction site        | kg             | 2.78E-05   |
| Oils, unspecified                          | kg             | 3.48E-09   |
| Transformation, from unspecified           | m <sup>2</sup> | 9.23E-07   |
| Transformation, to mineral extraction site | m <sup>2</sup> | 9.23E-07   |



# Appendix B – LCA Results

## B.1 Environmental Impact of Nickel Sulfate

Table B.1: Impact of producing 1kg nickel sulfate for ReCiPe midpoint impact categories.

| Impact category                            | Sulfate production | Metal refining | Primary extraction | Beneficiation | Ore mining | Total    |
|--|--------------------|----------------|--------------------|---------------|------------|----------|
| agricultural land occupation [m2a]         | 2.26E-02           | 7.75E-03       | 1.06E-01           | 6.43E-02      | 4.78E-02   | 2.48E-01 |
| climate change [kg CO2-Eq]                 | 2.66E-01           | 5.66E-02       | 2.31E+00           | 6.27E-01      | 6.60E-01   | 3.92E+00 |
| fossil depletion [kg oil-Eq]               | 1.54E-01           | 7.93E-03       | 7.64E-01           | 1.38E-01      | 1.45E-01   | 1.21E+00 |
| freshwater ecotoxicity [kg 1,4-DCB-Eq]     | 1.50E-01           | 7.56E-03       | 8.01E-02           | 1.04E-02      | 1.18E-02   | 2.60E-01 |
| freshwater eutrophication [kg P-Eq]        | 1.13E-04           | 1.52E-05       | 3.47E-04           | 7.49E-05      | 5.12E-05   | 6.01E-04 |
| human toxicity [kg 1,4-DCB-Eq]             | 1.50E+01           | 9.63E-02       | 5.59E-01           | 1.37E-01      | 6.87E-02   | 1.59E+01 |
| ionising radiation [kg U235-Eq]            | 2.94E-02           | 2.39E-02       | 9.72E-02           | 4.89E-02      | 4.65E-02   | 2.46E-01 |
| marine ecotoxicity [kg 1,4-DCB-Eq]         | 1.52E-01           | 8.75E-03       | 6.90E-02           | 9.26E-03      | 1.03E-02   | 2.49E-01 |
| marine eutrophication [kg N-Eq]            | 2.06E-04           | 3.45E-05       | 1.52E-03           | 5.17E-04      | 1.24E-03   | 3.51E-03 |
| metal depletion [kg Fe-Eq]                 | 7.23E-02           | 7.75E-03       | 1.50E-01           | 1.51E-02      | 2.38E-02   | 2.69E-01 |
| natural land transformation [m2]           | 7.99E-05           | 2.50E-05       | 1.43E-03           | 1.17E-03      | 8.21E-04   | 3.52E-03 |
| ozone depletion [kg CFC-11-Eq]             | 2.43E-08           | 6.60E-07       | 3.06E-07           | 6.94E-08      | 6.13E-08   | 1.12E-06 |
| particulate matter formation [kg PM10-Eq]  | 1.40E-03           | 6.59E-05       | 3.90E-03           | 9.76E-04      | 1.25E-03   | 7.60E-03 |
| photochemical oxidant formation [kg NMVOC] | 1.10E-03           | 4.96E-02       | 7.50E-01           | 1.40E-01      | 1.66E-01   | 1.11E+00 |
| terrestrial acidification [kg SO2-Eq]      | 5.88E-03           | 1.08E-04       | 1.35E-02           | 2.59E-03      | 2.66E-03   | 2.48E-02 |
| terrestrial ecotoxicity [kg 1,4-DCB-Eq]    | 3.76E-05           | 1.28E-03       | 1.56E-03           | 3.76E-05      | 3.05E-05   | 2.95E-03 |
| urban land occupation [m2a]                | 4.85E-03           | 6.62E-04       | 1.96E-02           | 4.56E-03      | 3.90E-03   | 3.35E-02 |
| water depletion [m3]                       | 1.91E-02           | 1.62E-04       | 2.35E-02           | 9.52E-04      | 1.35E-03   | 4.50E-02 |

## B.2 Environmental Impact of Cobalt Sulfate

Table B.2: Impact of producing 1kg cobalt sulfate for ReCiPe midpoint impact categories.

| Impact category                            | Sulfate production | Metal refining | Primary extraction | Beneficiation | Ore mining | Total    |
|--|--------------------|----------------|--------------------|---------------|------------|----------|
| agricultural land occupation [m2a]         | 7.35E-02           | 1.13E-02       | 1.53E-01           | 9.40E-02      | 6.99E-02   | 4.02E-01 |
| climate change [kg CO2-Eq]                 | 3.29E+00           | 9.34E-02       | 2.92E+00           | 7.11E-01      | 6.84E-01   | 7.69E+00 |
| fossil depletion [kg oil-Eq]               | 1.31E+00           | 1.16E-02       | 1.20E+00           | 2.02E-01      | 2.12E-01   | 2.93E+00 |
| freshwater ecotoxicity [kg 1,4-DCB-Eq]     | 6.62E-02           | 1.10E-02       | 1.16E-01           | 1.52E-02      | 1.72E-02   | 2.26E-01 |
| freshwater eutrophication [kg P-Eq]        | 7.06E-04           | 2.22E-05       | 4.64E-04           | 1.09E-04      | 7.49E-05   | 1.38E-03 |
| human toxicity [kg 1,4-DCB-Eq]             | 6.67E-01           | 1.41E-01       | 7.68E-01           | 2.00E-01      | 1.00E-01   | 1.88E+00 |
| ionising radiation [kg U235-Eq]            | 2.18E-01           | 3.50E-02       | 1.42E-01           | 7.15E-02      | 6.80E-02   | 5.35E-01 |
| marine ecotoxicity [kg 1,4-DCB-Eq]         | 5.91E-02           | 1.28E-02       | 1.00E-01           | 1.35E-02      | 1.50E-02   | 2.00E-01 |
| marine eutrophication [kg N-Eq]            | 2.28E-03           | 5.04E-05       | 2.23E-03           | 7.56E-04      | 1.81E-03   | 7.13E-03 |
| metal depletion [kg Fe-Eq]                 | 1.34E-01           | 1.13E-02       | 2.21E-01           | 2.21E-02      | 3.47E-02   | 4.23E-01 |
| natural land transformation [m2]           | 8.13E-04           | 3.65E-05       | 2.13E-03           | 1.70E-03      | 1.20E-03   | 5.88E-03 |
| ozone depletion [kg CFC-11-Eq]             | 8.17E-07           | 9.64E-07       | 5.33E-07           | 1.01E-07      | 8.97E-08   | 2.51E-06 |
| particulate matter formation [kg PM10-Eq]  | 5.59E-03           | 9.62E-05       | 5.62E-03           | 1.43E-03      | 1.83E-03   | 1.46E-02 |
| photochemical oxidant formation [kg NMVOC] | 4.94E-02           | 7.24E-02       | 1.10E+00           | 2.04E-01      | 2.43E-01   | 1.67E+00 |
| terrestrial acidification [kg SO2-Eq]      | 1.56E-02           | 1.57E-04       | 1.96E-02           | 3.79E-03      | 3.89E-03   | 4.31E-02 |
| terrestrial ecotoxicity [kg 1,4-DCB-Eq]    | 1.36E-04           | 1.87E-03       | 2.28E-03           | 5.49E-05      | 4.47E-05   | 4.39E-03 |
| urban land occupation [m2a]                | 2.23E-02           | 9.66E-04       | 2.76E-02           | 6.66E-03      | 5.71E-03   | 6.32E-02 |
| water depletion [m3]                       | 1.56E-02           | 2.36E-04       | 3.42E-02           | 1.39E-03      | 1.97E-03   | 5.35E-02 |

### B.3 Environmental Impact of Manganese Sulfate

Table B.3: Impact of producing 1kg manganese sulfate for ReCiPe midpoint impact categories.

| <b>Impact category</b>                     | <b>Sulfate production</b> | <b>Metal refining</b> | <b>Mining</b> | <b>Total</b> |
|--|---------------------------|-----------------------|---------------|--------------|
| agricultural land occupation [m2a]         | 6.25E-03                  | 1.78E-02              | 8.97E-04      | 2.49E-02     |
| climate change [kg CO2-Eq]                 | 7.28E-02                  | 1.07E+00              | 1.15E-01      | 1.26E+00     |
| fossil depletion [kg oil-Eq]               | 5.06E-02                  | 2.16E-01              | 4.23E-02      | 3.09E-01     |
| freshwater ecotoxicity [kg 1,4-DCB-Eq]     | 3.68E-02                  | 1.13E-02              | 1.35E-03      | 4.95E-02     |
| freshwater eutrophication [kg P-Eq]        | 3.21E-05                  | 3.54E-04              | 4.69E-06      | 3.90E-04     |
| human toxicity [kg 1,4-DCB-Eq]             | 3.54E+00                  | 3.55E-01              | 7.19E-03      | 3.90E+00     |
| ionising radiation [kg U235-Eq]            | 8.38E-03                  | 2.04E-02              | 5.79E-03      | 3.45E-02     |
| marine ecotoxicity [kg 1,4-DCB-Eq]         | 3.69E-02                  | 1.11E-02              | 1.03E-03      | 4.90E-02     |
| marine eutrophication [kg N-Eq]            | 5.97E-05                  | 5.74E-04              | 4.29E-04      | 1.06E-03     |
| metal depletion [kg Fe-Eq]                 | 2.04E-02                  | 1.14E-02              | 5.60E-03      | 3.73E-02     |
| natural land transformation [m2]           | 2.30E-05                  | 8.12E-05              | 3.75E-05      | 1.42E-04     |
| ozone depletion [kg CFC-11-Eq]             | 6.45E-09                  | 3.77E-08              | 1.66E-08      | 6.08E-08     |
| particulate matter formation [kg PM10-Eq]  | 5.35E-04                  | 2.27E-03              | 3.85E-04      | 3.19E-03     |
| photochemical oxidant formation [kg NMVOC] | 3.79E-04                  | 5.56E-01              | 1.29E-03      | 5.57E-01     |
| terrestrial acidification [kg SO2-Eq]      | 2.36E-03                  | 5.51E-03              | 7.82E-04      | 8.65E-03     |
| terrestrial ecotoxicity [kg 1,4-DCB-Eq]    | 1.29E-05                  | 2.74E-04              | 3.71E-04      | 6.58E-04     |
| urban land occupation [m2a]                | 1.37E-03                  | 1.05E-02              | 5.02E-04      | 1.24E-02     |
| water depletion [m3]                       | 4.53E-03                  | 1.55E-03              | 1.25E-04      | 6.20E-03     |

## B.4 Environmental Impact on TAP and PMFP

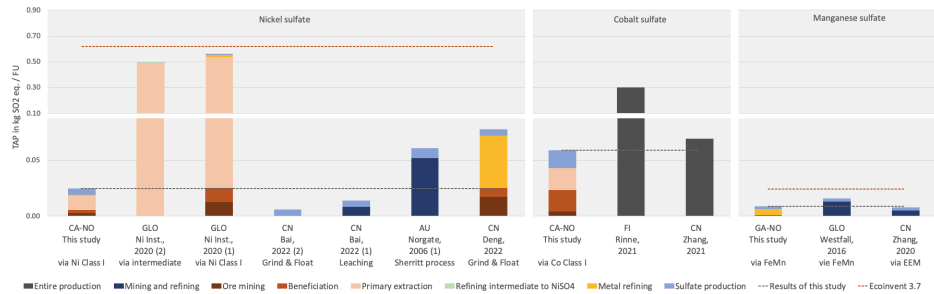


Figure B.1: Terrestrial acidification potential caused by producing nickel-, cobalt- and manganese sulfate. Results of this study in direct comparison to relevant literature.

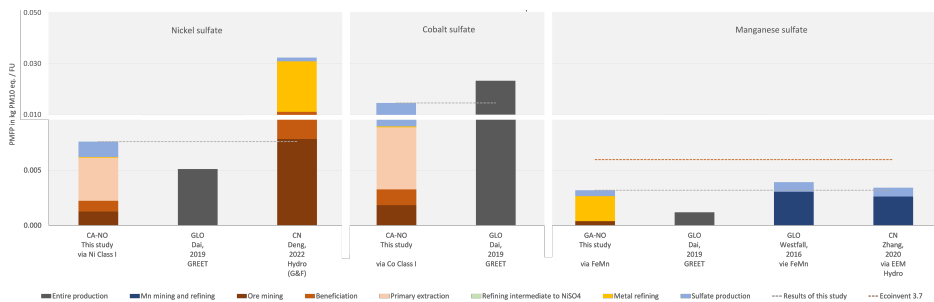


Figure B.2: Particulate matter formation potential caused by producing nickel-, cobalt- and manganese sulfate. Results of this study in direct comparison to relevant literature.

