Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Sara Khan

Parametric Life Cycle Modelling of Nickel Sulphate

Master's thesis in Industrial Ecology
Supervisor: Anders Hammer Strømman
Co-supervisor: Nelson Manjong

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EPT-P-2021

MSc thesis
for
student Sara Khan
Spring 2021

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Background and objective

Electrification is a promising option for the deep decarbonization of key land transport segments. How large climate change mitigation benefits electrification might yield is dependent on the footprint from the manufacturing of the vehicle, battery, and the electricity fuelling the car. The impacts from the production of the batteries have been a focal point of interest. Many studies point to significant upstream climate impacts from battery production. However, the variability in the results makes it difficult to conclude robustly on how to best proceed to improve the environmental performance of current lithium-ion batteries. A critical step along the battery value chain is producing high purity metals and high-grade battery chemicals. This is particularly important for battery precursor materials, predominantly in sulphates, oxides, or carbonates with significant purity levels. Nickel sulphate produced primarily via acid-leaching of class I nickel(99.9% nickel), nickel matte, and other secondary routes is the primary raw material for NCM batteries. With the advent of higher chemistries like the NCM811 and NCM955, the use of nickel sulphate becomes vital as a precursor material. Therefore, this work assesses the carbon footprints of nickel sulphate to increase robustness for life cycle assessments of batteries.

Aim and Scope

This thesis will investigate the footprints of nickel sulphate through a parametric attributional process-based model. Using parameters identified from the engineering literature, the thesis tests the effects of their variations on the overall footprints. In addition, the parametric modelling exercise provides a novel approach to understanding variability in LCA and gives a new technique in presenting several LCA simulations for a given functional unit. The thesis provides the student with a broader understanding of performing complex LCA modelling while simultaneously contributing to a larger scope of research within sustainable battery value chains.

The following tasks are then to be carried out during this thesis.

1. ***Literature review of Nickel Sulphate production routes***

This section reviews production routes for nickel sulphate and identifies the parameters that are likely to change the overall carbon footprints. Based on this understanding, a parametric life cycle model is developed.

2. ***Compilation of detailed Life Cycle Inventories (LCIs)***

Using the parametric model described in section 1, the student compiles and creates a parametric inventory model flexibility to testing specific value chain levers.

3. ***Application of Life Cycle Impact Assessment (LCA) methods***

In this section, the parametric model created in section 2 should assess the environmental impacts using the in-house modelling software ARDA. Levers tested should be within defined engineering ranges.

4. ***Analysis of the results***

The analysis of the results should compare the footprints (specifically greenhouse emissions) as a function of the lever combinations with details for each process in the value chain. The results of the thesis should capture how changes in the parameters produce changes in the overall footprints.

5. ***Documentation***

The findings of this research are expected to be documented according to the MSc thesis standards of EPT.

The work shall be edited as a scientific report, including a table of contents, a summary in Norwegian, conclusion, an index of literature etc. When writing the report, the candidate must emphasise a clearly arranged and well-written text. To facilitate the reading of the report, it is important that references for corresponding text, tables and figures are clearly stated both places. By the evaluation of the work the following will be greatly emphasised: The results should be thoroughly treated, presented in clearly arranged tables and/or graphics and discussed in detail. The candidate is responsible for keeping contact with the subject teacher and teaching supervisors.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

According to "Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU" § 20, the Department of Energy and Process Engineering reserves all rights to use the results and data for lectures, research and future publications.

Submission deadline: **11th June 2021**

☐ Work to be done in lab (Waterpower lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department for Energy and Process Engineering

Anders Hammer Strømman

Supervisor: Prof. Anders Hammer Strømman
Co-Supervisor(s): Nelson Manjong

Preface and Acknowledgements

This thesis, written at the Department of Energy and Process Engineering, is part of my M.Sc. in Industrial Ecology at the Norwegian University of Science and Technology. It was written in for the course of TEP4930 Industrial Ecology, in spring semester 2021.

I am immensely thankful to my supervisor Professor Anders Hammer Strømman and co-supervisor Nelson Manjong for their guidance, motivation, and support in this project. I am also grateful to the Industrial Ecology program and their employees for their support in this work. Lastly, I would like to especially thank my husband for his constant support, motivation, and tolerance throughout the semester in the Covid-19 times while in lockdown.

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List of abbreviations:

CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
BEV	Battery Electric Vehicles
EU	European union
EV	Electric vehicle
GWP	Global warming potential
HPAL	High Precipitate Acid Leaching
JRC	Joint Research Centre
LCA	Lifecycle Analysis
LCIA	Lifecycle Impact Analysis
LCI	Lifecycle Inventory
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
LIB	Lithium-ion Battery
LMO	Lithium manganese oxide
N_2O	Nitrogen dioxide
NCA	Lithium nickel cobalt aluminium oxide
$NiSO_4$	Nickel sulphate
NMC	Lithium nickel manganese cobalt oxide
SEI	Solid Electrolyte Interphase
SO_x	Sulphur oxides
NO_x	Nitrogen oxides
PM10	Particulate Matter size 10 micrometre

Abstract:

Constant growth of population is raising the energy demand as well as the environmental impacts and emissions from the use of this energy. To reduce these impacts and emissions, and to conform to the international agreements on climate change, many countries are adopting renewable energy sources for the power supply especially for electric cars. The increasing use of renewable energy and electric cars raises the demand for batteries. The actual goal of reducing the emissions by using renewable energy can only be met if the emissions from battery production are also low. Hence, reduction from battery production is a huge concern to actually lessen the environmental impacts.

One main concern from battery production is the Global Warming Potential (GWP) of batteries. Reducing the footprint of the inputs that go into the batteries can reduce the overall battery input. The data on metal supply for battery production is required to have a better traceability of emissions, so that the sustainable production of the inputs can take place. This thesis aims to study the environmental impacts of producing nickel sulphate through Lifecycle Assessment using a Parametric Model.

Some parameters that have an influence on the production of Nickel sulphate such as Ore grades, Mine-types, Electricity mixes and recovery efficiency from different stages i.e. beneficiation, primary extraction, refining, are chosen as free variables. In addition, the influence of allocation type on the results is also studied. 720 scenarios are formed with the combinations of different values for these six parameters. An inventory for each of the scenario is built that eventually generate 720 results from LCA. The level of influence of ore grade, mine-type, and recovery efficiencies on the GWP is studied for different electricity mixes that correspond to different regions. Ore grade and recovery efficiencies show a negative relation to the GWP for all the electricity mixes. The GWP for underground mine-type is higher than the open cast mine. Influence of Mass and economic allocation on the results are studied with respect to the electricity mixes as well as on different nickel sulphate production stages.

1 Introduction:

1.1 Background:

Increasing global population as well as the economic development all over the world has led to increased demand for capital. Industrial expansion, urbanization and global prosperity has increased resource use (Kuipers *et al.*, 2018). Not only these resources are limited but massive amount of energy is required in the extraction of these resources, production of capital, the use of this capital during its lifetime as well as the end-of-life treatment. The non-renewable resources such as fossil fuels are the most readily available energy sources that can be used after extraction and are being commonly used all over the world to meet the needs of the growing population. The extraction of these resources and their use is causing several environmental problems with climate change being the most alarming one. In addition, they cause several health issues leading to numerous social and economic adverse effects (Martins *et al.*, 2019). Professor Finn Gunnar Nielsen from Universitetet I Bergen in his presentation in SDG Conference 2018 UiB stated that fossil fuels make up around 78% of the total primary energy demand and hence contributing to almost 72% of the global greenhouse gas emissions (Gunnar Nielsen, 2018).

International agreements had been forming for the climate change mitigation. To conform to these international agreements such as the Kyoto Protocol by United Nations Framework Convention on Climate Change (UNFCCC) in 1997 and later Paris agreement (2015), local policies of countries are designed to comply with these agreements for lowering the carbon footprints of the countries. This creates the need to shift to the use of more renewable sources of energy that have significantly low carbon emissions. Renewable energy is the form of energy taken from geophysical, solar, or biological sources. These sources are generated by nature at a rate equal to or faster than their rate of use (Vega, 2015). Major renewable energy sources include Solar energy, Wind power, Hydro power, Geothermal energy, Tidal and Wave power, and biomass energy. These are the cleaner source of energy which not only produce minimum life-cycle emissions but also avoid any energy losses in terms of heat during the process of conversion of energy from one form to another such as chemical energy to mechanical energy. Many developed countries are shifting their major energy needs towards renewable sources of energy. These sources of energy will help countries to provide for the growing energy demand as well as help in managing the root cause of climate change.

Renewable energy is required to be substituted for fossil fuels which are majorly used for electricity/ heat production and transportation. Although using renewable energy for heat/electricity is the best source of energy, however these sources are not as predictable and consistent as using the fossil fuels. These energies are dependent on the natural occurrence of sun, wind, waves, and tides etc. At times massive energy is produced much more than what is required, and elsewise insufficient energy is produced. To bridge this gap between energy demand and supply, energy storage devices such as batteries are required. On the other hand, electrification of transportation is only possible with the use of batteries as a power supply source. Shifting to electrified transportation can reduce the emissions from transport sector to a great extent. Large scale use of renewable energy and reducing footprints by electrification of passenger cars is one of the EU policies for climate change mitigation (Climate change policies — European Environment Agency). As a result, several countries especially in Europe are now promoting the use of electric vehicles instead of internal combustion engines to reduce the use of fossil fuels for transportation. The market for electric vehicles is increasing both globally and especially in Nordic countries (Emilsson and Dahllöf, 2019). This increased demand for electric vehicles and other power storage in turn rises the demand for LIBs which are the power supply source for these vehicles hence a extremely crucial component. It is expected that by 2025, the production of LIB will grow three times more than the production in 2016 (Merriman, 2016). The LIBs not only influence the performance of the EV, but also has a great influence on its environmental impacts. With the increased demand of batteries that environmental impacts of batteries are bound to increase many folds, posing a threat to the environment in numerous ways. This creates the need to study the impacts of battery production in detail so they can be reduced.

1.2 State of the Art:

1.2.1 Electric Vehicles Battery:

Even though the use phase of the electric cars is the most significant phase, but battery manufacturing also takes up around 5-10% of the impacts including Global Warming Potential (GWP) (Schmidt *et al.*, 2016; Amarakoon *et al.*, 2013; Hawkins *et al.*, 2013). Notable number of studies have been done on the lifecycle of Electric Vehicles (EV) and the batteries used in them including (Emilsson and Dahllöf, 2019; Kelly *et al.*, 2019; Amarakoon *et al.*, 2013; Hawkins *et al.*, 2013). Emilsson and Dahllöf, (2019) state that since Battery production is the most energy intensive process in the production of Battery Electric Vehicles (BEV), so they have attempted to figure out the cause of high energy use in battery production. The battery capacity of 61 to 106 kg CO_2 e/kWh was estimated for Nickel Manganese Cobalt Oxide (NMC) batteries, and the difference was due to the different energy mixes as well as the temperature and humidity of the geographical location. Another study (Kelly *et al.*, 2019) looks at the production of NMC batteries around the world considering the regional differences at several stages including nickel refining, alumina reduction, NMC cathode production, battery cell and battery management systems. Amarakoon *et al.* (2013) identify materials or processes used in the lifecycle of a LIB that impact human health and environment the most. This study uses primary data from manufacturers and perform LCA to identify products for manufactures that have low impact on the environment as well as identify the areas of improvement in Production of LIB. Whereas Hawkins *et al.* (2013), shows a comparison between the EVs and the conventional cars across various impact categories. The GWP of the EVs is significantly lower than the conventional cars however, this study shows that the production phase of these cars exposes humans and the environment to many risks which includes ecotoxicity, human toxicity, resource depletion. Most of these are from the battery production. These risks are not present in conventional cars making the comparison tough between both the types. This creates the need to reduce the impacts from the supply chain of EVs so to make these preferable by reducing the risks. Another study (Dai *et al.*, 2019) discusses the environmental impacts of the LIBs through LCA taking into account the energy use and emissions such as SO_x, NO_x, PM10 and water consumption of the NMC batteries. They found out that the main contribution the NMC battery production is from the active cathode material, aluminium, and energy use. However, it was also established that the location of production and the place from where the material is sourced also has a great influence on the impact of batteries.

1.2.2 Nickel:

The footprint of Lithium-ion batteries is significantly influenced by the active cathode material. The primary extraction and beneficiation of cathode material which includes Cobalt, Nickel, Manganese, and phosphate, produces around 10-40% of the battery production impacts (Schmidt *et al.*, 2016; Amarakoon *et al.*, 2013; Hawkins *et al.*, 2013). Different battery chemistries are present including Lithium cobalt oxide (LCO), Lithium manganese oxide (LMO), Lithium nickel manganese cobalt oxide (NMC), Lithium iron phosphate (LFP), Lithium nickel cobalt aluminium oxide (NCA) and Lithium titanate (LTO). Each chemistry has its own characteristics. (Saldaña *et al.* 2019) shows a comparison of the well-known lithium ion batterie in terms of some characteristics such as safety, performance, lifespan, cost, specific energy, and specific power. According to the paper, the specific energy which refers to the energy density or the energy per unit mass, is the highest for LCO, MNC and NCA. However, LCO batteries are impractical to use due to the Solid Electrolyte Interphase (SEI[1]) and toxicity issues (Saldaña *et al.*, 2019). Both NCA and NMC are well-known for high energy density and in turn longer driving range ('Downstream nickel sulphate study update', 2019). However, as compared to NCA, NMC have overall better characteristic as they are better priced and much safer. Hence, NMC's are the most used batteries (Emilsson and Dahllöf, 2019).

To study the impacts of the Lithium-ion batteries (LIBs), it is important to narrow the study down to the impacts of the materials that go into the LIBs. Reducing the footprint of these materials can influence the impacts of the LIBs to a great extent. One of these materials is nickel. Nickel is used in cathode part of batteries as nickel sulphate which is a chemical form of nickel ('Downstream nickel sulphate study update', 2019). Nickel-based batteries NMC and NCA batteries are the most promising batteries as they have high capacity and low cost (Bak *et al.*, 2014) proportion of Nickel is also increasing in the NMC batteries because of improvements in the battery technology. The demand for Nickel is also increasing as a result of increased demand for NMC batteries as well as the increasing proportion of nickel in these batteries ('Downstream nickel sulphate study update', 2019). Further, according to (Schmidt *et al.*, 2016; Dai *et al.*, 2019) batteries containing nickel and cobalt have higher emissions as compared to other batteries due to the production of primary metals. Hence, the focus of this study is on environmental impacts of nickel sulphate production which is a nickel product used in batteries.

(Dry *et al.*, 2019) studies the environmental aspects of Nickel Sulphate production for the use in LIBs through hydrometallurgical processes. The study explains several routes to produce nickel sulphate such as HPAL, Caron, Goro and RKEF for producing intermediate products from limonite ore and then using various other routes for producing nickel sulphate

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[1] Solid Electrolyte Interphase (SEI) is formed when the decomposed electrolyte containing molecules attach to the surface of electrode (Stephan, 2019).

from the intermediate products. They state that if CO_2 and Water use is to be accessed then it is important to take the full processing route into account. Another study, ('Downstream nickel sulphate study update', 2019), shows a new commercially feasible conversion process of nickel-cobalt sulphide concentrate into nickel sulphate. This process produces high quality nickel sulphate, with higher metal recovery, low cost, low waste, lower emissions and less power consumption. (Harris, 2019) studies the links in Nickel, copper and cobalt markets and investigate the production of these metals for the use in LIBs. The challenges in production of Nickel are also discussed with regards to the laterite ores as sulphide ores are becoming depleted. In (Schmidt *et al.*, 2016), the most common up-stream production process routes of nickel and cobalt products that are used in the production of LIBs are studied as well as the global flow charts of these products. In addition, the current production shares of the products for LIBs were studied through Material Flow Analysis (MFA). The production processes at different stages happening at different locations globally are studied to understand and improve environmental impact assessment. A report for Joint Research Centre (JRC), the European Commission's science and knowledge service "Study on future demand and supply security of nickel for electric vehicle batteries" (Fraser *et al.*, 2021) is an extensive study on the supply security of Nickel which is used in the production of batteries in the form of Nickel sulphate. The objectives of the study included the assessment of EU's ability to internally source own nickel as well as to define a strategic approach to form a circular economy for EV Batteries. A twenty years' time-horizon was taken until 2040 to forecast nickel supply and the bottlenecks in the supply chain of nickel. Their main findings are that the global demand for nickel is expected to increase by 2.6Mt in next twenty years where the largest user of nickel will be the automotive industry. The main bottleneck to produce nickel sulphate is the availability of proper feedstock such as Class I nickel and intermediates. This can cause structural deficit around 2027. By 2030, battery recycling will become the main source of nickel sulphate. The research paper Energy Consumption and Greenhouse Gas Emissions of Nickel Products (Wei *et al.*, 2020), analysed the mass and energy balance based process model for four nickel products through case studies to make improvements in nickel production sustainability. The associated GHG emissions of these products are 14 tCO_2-eq/t alloy for nickel metal, 30 t CO_2-eq/t alloy for nickel oxide, 6 tCO_2-eq/t alloy for ferronickel, and 7 t CO_2-eq/t alloy for nickel pig iron. Flash smelting for extracting sulphide ore has resulted to be the optimum process for producing one ton contained nickel. However, using renewable energy power electric furnace for laterite ore smelting can be a promising method (Wei *et al.*, 2020). The LCA of nickel production in China has been studied in (Deng and Gong, 2018) and improvement suggestions are provided for the environmental hotspots that have been pointed out in the study. According to the paper the largest impact per kg electrolytic nickel is from FDP which is 4.68 kg oil-eq and the second largest is the GWP being 26.9kg CO_2-eq. the paper mentions that smelting is the most energy and emission intensive process for producing electrolyte nickel contributing to around 52.18% of the total impacts.

1.3 Research gap:

The incorporation of nickel production process into the impact evaluation of batteries production and recycling is important but there are many restrictions to it. Different types of nickel products have a lot of variation in their chemical and physical properties and are used for different purposes (Schmidt *et al.*, 2016). It is crucial to understand what type of products are used in batteries so their LCA can be performed. A study ‘Energy Consumption and Greenhouse Gas Emissions of Nickel Products’ (Wei *et al.*, 2020) reports several nickel production LCA studies and states that the GHG emissions and energy consumption are influenced by factors such as ores, process routes, nickel product and system boundaries. There is some research available for nickel sulphate production that focus on specific type of production but a holistic approach that captures the differences in the environmental impact caused by the influential factors is absent. This constrains the use of many LCA studies as they do not fit into the scenario at hand. A research is required that shows how different factors impact the LCA results to show how the GWP is altered with the change in these factors that are also referred to as ‘Parameters’ in this study. This type of study will facilitate the understanding of the relations between different factors so that assumptions can be made about a specific scenario at hand with the help of other LCA study.

1.4 Aim and Objective:

Nickel sulphate has been studied in this report based on the following reasons. Firstly, the cathode materials of the battery have the most influence on the environmental impacts of the batteries. Secondly, the most common and successful type of battery cathode chemistries are the ones with nickel. Thirdly, the proportion of Nickel in increasing in the NMC batteries with the technology improvements. And lastly, nickel products can decrease energy utilization and environmental impact of products through their use (Mistry *et al.*, 2016). This means that the demand of nickel is bound to increase in near future. It is necessary to study the lifecycle of the materials used in battery production to understand the actual impacts of batteries.

Even though nickel sulphate is a significantly crucial component of LIBs but there are few studies available that research the lifecycle of nickel sulphate. This study aims to provide:

1. environmental assessment of Primary Nickel sulphate production, highlighting the hotspots of environmental impacts within the value chain.
2. Parameterization of certain factors that can influence the impacts of Nickel sulphate production.
3. Study the Global warming potentials of these parameters in relation with the regionalized electricity mix.
4. Study the influence of allocation type used for partitioning the flows.

For this, a complete Lifecycle Assessment of Nickel Sulphate production through parameterization modelling is performed. The purpose of this research is to bridge the gap in the knowledge of Nickel sulphate production impacts which later contribute to the impacts of batteries. This report will not only provide the lifecycle environment profile of globally produced nickel sulphate but will also show how different factors affect the emissions intensity through parameterization.

2 Nickel Sulphate Production:

Nickel is the metal of affluent societies as unlike other metals that are typically used in construction and electricity conduction, it is used in technologies (Eckelman, 2010). The countries producing high amounts of nickel include Canada, Australia, China, Indonesia, Philippines, Russia, and New Caledonia (Wei *et al.*, 2020). The highest demand for nickel is in LIBs and stainless-steel production (Fraser *et al.*, 2021). It is expected that the demand of nickel from battery industry can reach up to 36% of the total nickel demand by 2030 (Fraser *et al.*, 2021).

There are various types of nickel chemicals that vary according to their composition and nickel content. Nickel sulphate is one of the nickel chemicals (Schmidt *et al.*, 2016). Nickel sulphate is an inorganic compound, and its chemical formula is denoted as $NiSO_4$. It is commonly used in battery production specifically in the cathode material of the battery. Figure 1. Battery Value Chain

shows the main components of a LIB and the path where nickel sulphate is used is highlighted in green.

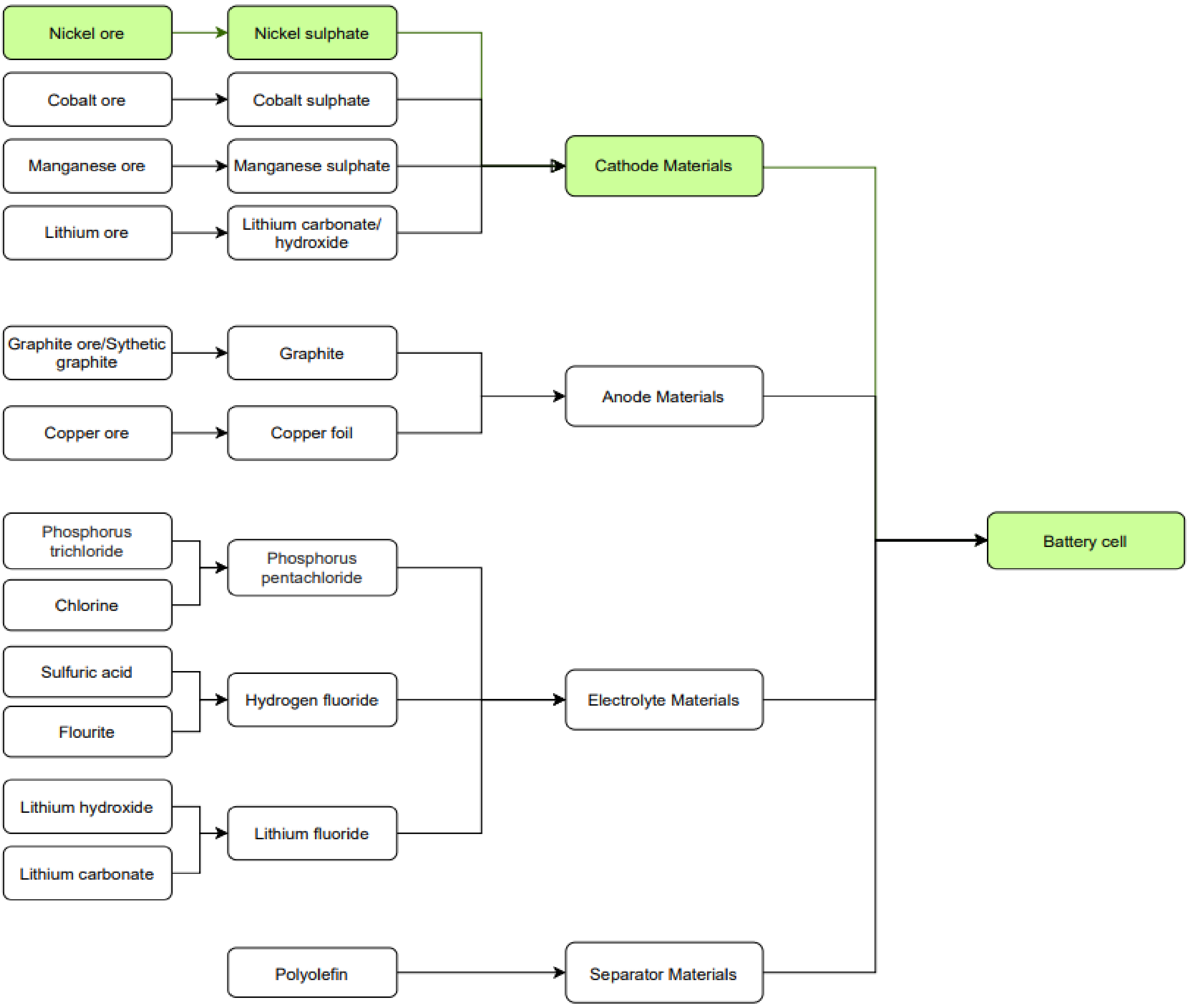

Figure 1. Battery Value Chain

Nickel sulphate production is done through variety of methods that are dependent on various factors such as ore type, mine type, and methodology etc. The base data (Gediga and Boonzaier, 2020) used in this study takes into account all the production methods. The data is presented as an average of the inputs from different sources. In this study, four general stages i.e., mining, beneficiation, primary extraction and refining of nickel sulphate production are considered that represent data from all routes for the primary production of nickel sulphate.

2.1 Mining:

All the processes until the ore preparation are included in the mining stage. The output from this stage are the ores containing nickel from all routes. The ore-types and mine-types used to produce nickel are explained.

2.1.1 Ore-type:

Nickel is produced from either laterite (oxidic) or sulphide ores. Laterite ores are generally found in areas with tropical climate and are oxidic in nature whereas the sulphide ores are mostly found with the copper ores and usually from underground mines (Gediga and Boonzaier, 2020)(Wei *et al.*, 2020). The energy demands for processing both types of ores differ. The shape, depth and location of the ore also have an influence on the energy demand for processing them (Mistry *et al.*, 2016). Sulphide ores have higher sulphur content which reduces the required amount of energy needed to heat the ore while in laterite ores the moisture is higher hence 3-5 times more energy than the sulphide ores is required for their processing (Schmidt *et al.*, 2016). Even though most of the production is done through sulphide ore but the production from laterite ore has been increasing in the past and the trend seems to continue. In addition, the ore grade of nickel is bound to decline with time for a specific production site. This means that the good quality ores start depleting and only the less rich ones remain which increases the demand of energy required for processing these ores.

2.1.2 Mine-type:

Two mine types are present, Open-cast, and Underground mines. Open-cast mining is done when the resources are found close to the surface of the ground while underground mining is done to extract resources from below the earth surface. The electricity requirement for underground mining is much higher than the open cast due to the extensive drilling, removing water, lifting rock up to the surface as well as ventilation (Eckelman, 2010)(Mining Industry Energy Bandwidth Study, 2007). Whereas liquid fuel requirement for open cast mines is higher than the underground mines as more transport of rocks from the pit is required through trucks (Eckelman, 2010).

2.2 Beneficiation:

This stage consists of ore preparation for laterite ore and concentrate production for sulphide ores. Ore preparation includes crushing, grinding, and drying of the ores as laterite ores are high in moisture. While in concentrate production, magnetic separation or flotation is used to produce nickel concentrate.

2.3 Primary extraction:

At this stage, the nickel concentrate is converted into nickel matte and the prepared ore into mixed sulphide. Two processing technologies are used to produce nickel, Hydrometallurgy for laterite ores through high-pressure acid leaching HPAL and Pyrometallurgy for sulphide ores through flash furnace (Eckelman, 2010). According to (Gediga and Boonzaier, 2020) both hydrometallurgy and pyrometallurgy can be used for both the types of the ores. Which implies there are four production ways of nickel sulphate. It can also be produced as a by-product from precious group metal production or through secondary production.

Figure 2 shows four ways to produce nickel which are laterite ore with hydrometallurgy, laterite ore with pyrometallurgy, sulphide ore with hydrometallurgy and sulphide ore with pyrometallurgy.

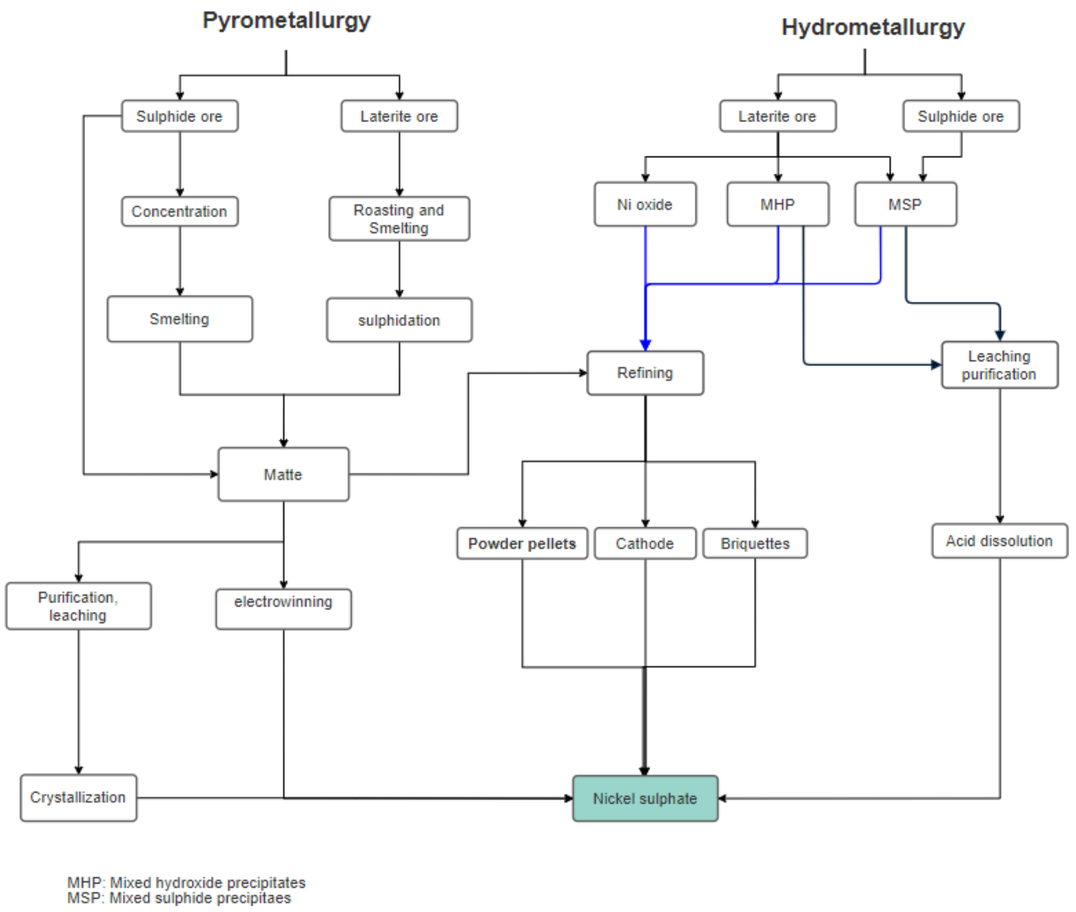

*Figure 2. Nickel sulphate production routes (*Schmidt *et al.*, 2016*; 'Downstream nickel sulphate study update', 2019)*

Commonly sulphide ores are treated with pyrometallurgy, and laterite ores are treated with hydrometallurgy. In pyrometallurgy after mining of sulphide ores, concentration is performed which gives the output as nickel concentrate. This is then followed by flash or electric smelting that produces nickel matte. For laterite ore being treated by pyrometallurgy, sulphidation is done before it is converted to matte.

On the other hand, in hydrometallurgy the main techniques are High Pressure Acid Leaching (HPAL), Goro and Caron process. Caron process requires large amount of energy and results in lower recovery efficiency hence its mostly avoided (Schmidt *et al.*, 2016). HPAL is a leaching process which also consists of sulphur burning acid plant providing high pressure steam, power and concentrated sulphuric acid that is used in further processes. The intermediate product from HPAL is Mixed Hydro Precipitates (MHP) from laterite ores (Dry *et al.*, 2019) while Mixed Sulphide Precipitates (MSP) from sulphide ores are obtained from solvent extraction (‘Downstream nickel sulphate study update’, 2019). Although not very common, the third process Goro produces nickel oxide as the intermediate process for production of nickel sulphate (Dry *et al.*, 2019).

2.4 Refining:

Nickel matte and mixed sulphides are refined to produce nickel sulphate also known as nickel sulphate hexahydrate but is referred to as just nickel sulphate in this paper. The matte produced can be refined by either electrowinning or through hydrometallurgical leaching, purification, and crystallization to produce nickel sulphate (Schmidt *et al.*, 2016).

3 Methodology

Life cycle assessment can be defined as a tool for evaluating and assessing environmental impacts arising from the life cycle of a product or a service at different stages from its production to its disposal (Kuipers *et al.*, 2018; Dong *et al.*, 2020). To be able to thoroughly understand the influence a certain activity has on the environment, it is necessary to quantify its impacts through LCA. The four stages of LCA include definition of goal and scope, formation of inventory (LCI), assessment of impacts (LCIA) and interpretation of the results. Figure 3 illustrates these phases as described by ISO 14040. This framework requires that no judgement to be made before all the stages are complete as these are interdependent on each other, and none give an absolute result independently.

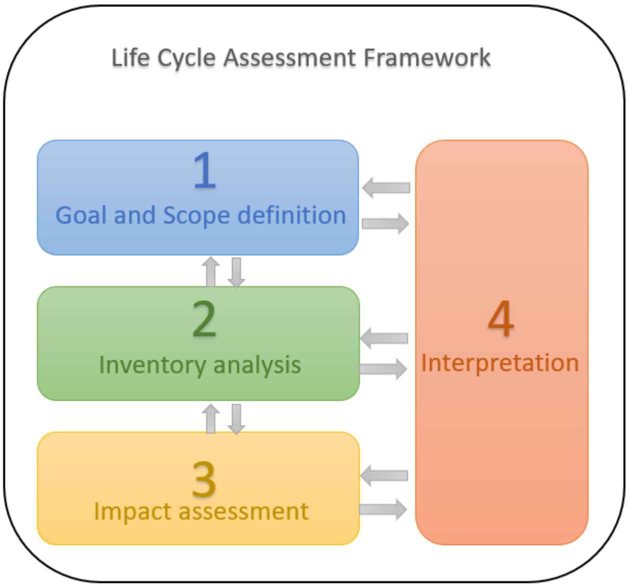

Figure 3. LCA Framework

3.1 Goal and Scope:

Starting a Lifecycle Assessment requires an unambiguous definition of the aim/goal of the study. The methodology and the context are also pre-decided. System boundaries are determined such as from what point of the chain the study starts and ends and what processes are included. Functional unit is decided which is the reference output produced as the result of the study. It is an important part of the LCA study as the results are expressed in terms of the functional unit such as in this study the functional unit is 1 kg nickel sulphate and the results will be the impacts per kg of Nickel sulphate. The impact categories are also decided that are to be studied through the research.

3.2 Inventory Analysis:

The second stage consists of collection and analysis of Lifecycle Inventory. According to (ISO 14044:2006(en)), it is the "compilation and quantification" of the flows in the lifetime of a product. The inventory consists of the flows coming in or going out of the system boundary. These flows consist of materials, energy, waste, resources as well as the stressors. The data is with respect to the functional unit for example, how much energy and material are required for the production of 1 kg of Nickel sulphate and what are the subsequent emissions and wastes generation.

The inventory analysis requires that the data be tailored for the use in assessment. In order to have the results per functional unit, scaling the data according to the functional unit is required. Other than scaling, co-production and by-products also need to be eliminated from the system through allocation.

The processes for producing functional unit are divided into 'Foreground' and 'Background'. The foreground consists of all the processes within the boundaries of the system. While background consists of all the flows from the processes outside the system boundaries. A requirement or co-efficient matrix 'A' is developed that tells us what is required to produce 1 functional unit and how much is required. The dimensions of this matrix are process by process. This matrix is divided into four parts depending on the flows to and from the foreground and the background systems (Strømman, 2010).

$$A = \begin{bmatrix} A_{ff} & A_{fb} \\ A_{bf} & A_{bb} \end{bmatrix}$$

(Eq. 1)

A_{ff} includes the flows within the foreground, A_{fb} consists of flows from the foreground to the background. These flows are mostly equal to zero. A_{bf} contains flows from the background to the foreground system. A_{bb} are the flows that are required by the background from the background system.

3.3 Impact assessment

This phase consists of "understanding and evaluating" the environmental impacts from the Lifecycle of the product. It provides information about the inventory flows through contribution analysis to better understand their environmental significance and find the emission hotspots. In addition to quantifying the damage, this stage also makes it possible to compare different sources of damage (Hauschild and Huijbregts, 2015). The three main steps of impact assessment are presented in Figure 4.

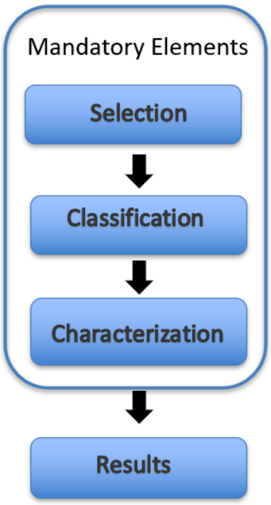

Figure 4. Mandatory elements of Lifecycle Impact Assessment (Hauschild and Huijbregts, 2015)

First step includes selecting the impact categories, indicators, and characterization models, second step consists of assigning (classifying) the elementary flows to impact categories which they contribute to. In the last step, characterization factors are multiplied with the classified elementary flows in order to convert them in quantitatively comparable terms. An example of impact assessment from this study is that N_2O (kg/ functional unit) is emitted as a result of Nickel sulphate production. At the midpoint impact category, it is assigned to climate change which is the impact it contributes to. Lastly for characterization, impact scores are assigned to characterization factor such as CO_2-eq. so, N_2O is converted into CO_2 equivalent terms.

In practical the calculations for LCA are performed through linear algebra and matrices. The total output from the system is denoted as x-vector which is same as total demand. It is equal to the sum of external demand from buyers (y) and intermediate demand (Ax). Ax is a matrix achieved from the multiplication of requirement matrix and the total demand matrix (Strømman, 2010). This gives the equation:

$$x = Ax + y$$

$$\begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} = \left[\begin{pmatrix} A_{11} & \cdots & A_{1,pro} \\ \vdots & \ddots & \vdots \\ A_{pro,1} & \cdots & A_{pro,pro} \end{pmatrix}\right] \begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} + \begin{bmatrix} y_1 \\ \vdots \\ y_{pro} \end{bmatrix}$$

(Eq. 2)

The dimensions of both ‘x’ and ‘y’ are $(pro \times 1)$ which means the rows consist of all the processes. The equation can then be solved for x:

$$x = (I - A)^{-1}\, y$$

$$\Rightarrow \; x = \mathrm{Ly}$$

(Eq. 3)

Here L, Leontief inverse, is the matrix of external demand and I is the identity matrix. The vector for stressors denoted as ‘e’ shows the stressors produced per unit external output. It is calculated by multiplying the stressors intensity matrix ‘S’ (extracted from the inventory) with the total output x. The term stressor not only refers to the emissions produced but also to other environmental loads associated to the production. The stressors intensity matrix describes what environmental stressors are associated with the output of each process. The dimensions of the stressors’ matrix are stressors by processes (str x pro) which means the rows consists of the stressors and the columns represent the processes (Strømman, 2010).

$$e = Sx = SLy$$

$$\begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} = \left[\begin{pmatrix} S_{11} & \cdots & S_{1,pro} \\ \vdots & \ddots & \vdots \\ S_{str,1} & \cdots & S_{str,pro} \end{pmatrix}\right] \begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix}$$

(Eq. 4)

The impact score can then be calculated for the contribution analysis. For this, characterization matrix ‘C’ is required that contains the characterization factors. The characterization factors take the stressors having same environmental impact and express them in equivalent terms. The dimensions of the C matrix are impact category by stressors (imp x str) which means the rows represent the impact categories while the columns show the stressors. The stressors can contribute to more than one impact category so there can be more than one entry for each stressor. The C-matrix can be multiplied by the e-vector to get the total impacts per unit external demand vector ‘d’.

$$d = Ce$$

$$\begin{bmatrix} d_1 \\ \vdots \\ d_{imp} \end{bmatrix} = \left[\begin{pmatrix} C_{11} & \cdots & C_{1,str} \\ \vdots & \ddots & \vdots \\ C_{imp,1} & \cdots & S_{imp,str} \end{pmatrix}\right] \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix}$$

(Eq. 5)

The contribution of each process to the impacts denoted as D_{pro} can be calculated by multiplying the C-matrix with E-matrix. E matrix is a matrix achieved by multiplying the S-matrix with the diagonalized x-vector denoted as $\hat{x}$.

$$D_{pro} = CE$$

(Eq. 6)

where,

$$E = S\hat{x}$$

Hence the matrix provided, and the matrix deduced from calculations are presented Table 1.

Table 1. Matrices, vectors, and sets used in Contribution Analysis (Strømman, 2010).

Sets		**Description**
pro		Processes
str		Stressors
imp		Impact categories
Matrices	**Dimensions**	**Description**
A	$pro \times pro$	Matrix of inter process requirements
y	$pro \times 1$	Vector of external demand of processes
x	$pro \times 1$	Vector of outputs for a given external demand
L	$pro \times pro$	The Leontief inverse, Matrix of outputs per unit of external demand
S	$str \times pro$	Matrix of stressors intensities per unit output
e	$str \times 1$	Vector of stressors generated for a given external demand
E	$str \times pro$	Matrix of stressors generated from each process for a given external demand
C	$imp \times str$	Characterization matrix
d	$imp \times 1$	Vector of impacts generated for a given external demand
D_{pro}	$imp \times pro$	Matrix of impacts generated from each process for a given external demand

3.4 Parametrization:

A parametrization model in LCA is a model that helps to study the influence of dynamic parameters on the impacts of the product under study. This model can be used for the optimization of a process by reducing energy use and emission intensity by only changing defined set of parameters. There are no definitions for parametric model or parameterization in LCA defined by the ISO 14040 and ISO 14044 (Kozderka *et al.*, 2017). According to (Kozderka *et al.,* 2017), it can be defined as 'a model based on the fixed set of parameters' or as a 'stable model where user can only change some free parameters'. On the other hand, (Niero *et al.*, 2014), describes parameterization as replacement of computed numbers with raw data and formulas in unit process dataset.

There is no set way of performing parameterization in LCA. In this study, factors/parameters that affect the energy use and emission intensity of production are selected for the assessment. The parameters can be anything that has an influence on the environmental impact of a product. For example, quality of nickel ore grade influences how much energy is used in the production of nickel so, with parameterization we change the quality of ore grade within a certain range and see how the relative change in ore grade changes the environmental impact of the final product that is nickel.

Based on these parameters, different scenarios are formed with combinations of different values for each parameter. The base inventory is then altered according to each set of parameters forming a different inventory for each scenario. LCA for each scenario is performed. The results from all of these LCAs are achieved in the form of numeric values where each result have massive amount of information that can be extracted. The information relevant to the goal of the study is then collected from the results of each study and is presented in ways that makes it possible to compare how the selected parameters have affected the results.

3.5 Interpretation:

Interpretation is the final stage where the LCI and LCIA results are examined and summarized (ISO 14040:2006(en)). The results from the assessment are in numeric terms with a lot of information. This massive information in numeric terms need to be translated so they can be understood more clearly and be used to draw conclusions and use the results for decision making.

The results from the parametric model are usually presented in the form of figures and diagrams that show the ranges or trends of how the change in parameters changes the results. This deduced information can then be used for various purposes such as decision making.

4 Case Description:

4.1 Goal and scope:

The goal of this study is to investigate the production process of nickel sulphate and to build a parametric LCA model to examine the change in environmental impacts of nickel sulphate due to the change in factors such as ore grade, mine type, electricity mix, and recovery ratios from different stages of processing. The results from this report can be utilized further in the impact assessment of products that use nickel sulphate produced with specific characteristics.

The system boundaries are set from cradle to gate which means that all the stages from mining to the production of finished product that goes out of the factory gate are considered. The data for LCA of Nickel sulphate primary production was collected according to the technical framework of LCA where the functional unit is 1 kg of nickel sulphate and the content of nickel in 1 kg nickel sulphate is around 22% (Gediga and Boonzaier, 2020). The data used comprise of nickel sulphate produced from all four routes of producing nickel mentioned in section 2.3 as an average of all the processes. The stages of nickel sulphate production, in this study, are broadly categorized as four processes: mining, beneficiation, primary extraction and refining. The output from these stages are nickel ore, nickel concentrate, nickel matte and nickel sulphate, respectively. Each of the stage is treated as a ‘black box’ where each stage’s inputs and outputs are not interdependent. Figure 5 shows the production system of nickel sulphate with the system boundary for this study, The purple dotted line shows the system boundary. The flows into the system are the inputs from the background processes while inside the boundary all the foreground processes are considered.

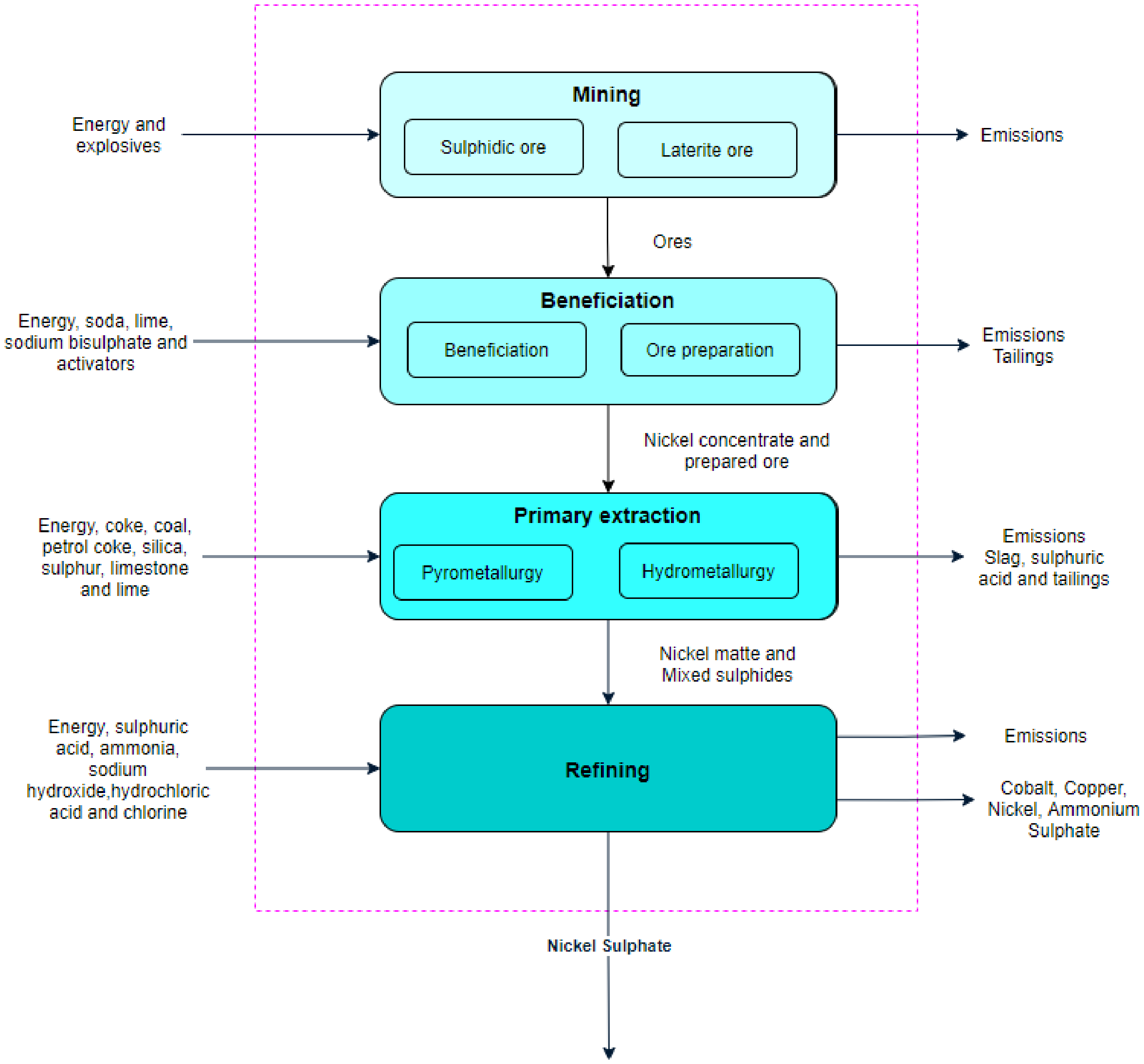

Figure 5. Overview of Nickel sulphate production

And lastly, the target audience of this paper can include academia, LCA practitioners, NGOs and public.

4.2 Inventory Analysis:

In this study, investigation of the production processes of Nickel sulphate and its value chain consists of a comprehensive literature research. Data from different sources were accessed to be used in the Lifecycle Inventory (LCI). According to (Schmidt *et al.*, 2016), the LCI datasets for nickel are provided by Ecoinvent, GaBi, and the scientific studies by the Nickel Institute and CSIRO but none of these can be used in a battery LCA as either their functional units are different or they are specific to one nickel or cobalt product. Hence, a thorough literature research was done to extract the data. There are several factors that influence the inputs and outputs into the processes so there are a lot of variations in the data from the literature. Some of the sources that were initially considered included (Deng and Gong, 2018; Wei *et al.,* 2020; Mistry *et al.,* 2016; Norgate and Rankin, 2000) however, the data in these studies was either too specific for one case or did not cater to the needs of this study. In this case the LCI from 'Life Cycle Assessment of Nickel Products' which is a report commissioned by the Nickel Institute (Gediga and Boonzaier, 2020) provided a decent source for base inventory that was elaborate enough to be used in an LCA assessment of nickel sulphate. From the report the data for nickel sulphate production was extracted. In addition, data from (Eckelman, 2010) and other data mentioned above were used to fill the gaps and to adjust the data so it is suitable for the parameterization model in this study.

The nickel sulphate production model from 'Life Cycle Assessment of Nickel Products' (Gediga and Boonzaier, 2020) has a cradle to gate system boundary, where data from both hydrometallurgical and pyrometallurgical routes and both ore types sulphide and laterite ores is considered. The nickel content is 22% in nickel sulphate produced in this model. Geographically the scope is global (minus China) including 15% of the total global nickel production which makes up 105,000 tons. China accounts for around 31% of the global nickel production but this is not represented in the study as the data from China was unavailable.

4.2.1 Allocation:

The nickel sulphate production model is a Multiple product output model and hence produces some co-products and by-products as well which includes some precious metals, base metals, and non-metals. In order to have an inventory that provides an impact assessment solely for Nickel sulphate, applying allocation is required. According to ISO 14044:2006(en) Allocation is defined as

> "Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems".

Partitioning approach for allocation has been used in this study. According to (Cherubini, Strømman and Ulgiati, 2011) this method consists of artificial splitting of a multi-functional process so it becomes an independent single function process. This method is only possible to be done theoretically. In practice it would mean that the impacts are divided between the coproducts.

From Nickel sulphate model in (Gediga and Boonzaier, 2020), the outputs that leave the system include 0.044 kg Cobalt, 0.71 kg copper, 2 kg Nickel, 0.89 kg Ammonium sulphate and 1 kg Nickel sulphate. In this study, both mass and economic allocation was performed separately on the LCI data.

- *Mass Allocation:*

Mass allocation allocates the inputs and outputs based on the weight of their mass. The coefficient for mass allocation was determined by:

$$C_{mass} = \frac{m_{NiSO_4}}{m_{total}}$$

(Eq. 7)

where,

$$m_{total} = m_{NiSO_4} + m_{co-products}$$

(Eq. 8)

Here,

C_{mass} is the coefficient of mass,
m_{NiSO_4} is the mass of nickel sulphate,
$m_{co-products}$ represents the mass all the other co products.

In other words, from the total output in kilograms, the percentage of nickel sulphate was 22%, so the coefficient of nickel sulphate mass allocation is 0.22 and all the inputs, outputs and energy values are allocated according to this coefficient.

- *Economic Allocation:*

Economic allocation allocates the inputs and outputs based on their economic cost. This type of allocation is important as some precious metals have low production volume but high price. allocating the impacts according to mass will not justify the need to produce these materials (Gediga and Boonzaier, 2020).

Some of the co-products in this study also have higher than the other materials such as the price for Cobalt is much higher than the price for ammonium sulphate. The prices of the outputs from the model are:

Table 2. Prices for the Nickel sulphate and other co-products

Output	Price ($/kg)	References
Cobalt	52.76	(London Metal Exchange)
Copper	9.05	(London Metal Exchange)
Nickel	16.16	(London Metal Exchange)
Ammonium sulphate	0.17	(Ammonium Sulfate Market Size | Global Industry Report, 2027)
Nickel Sulphate	2.23	(Battery nickel price regains premium over metal)

The coefficient of economic allocation can be determined by:

$$C_{eco} = \frac{P_{NiSO_4} \times m_{NiSO_4}}{\sum_{i=1}^{n} P_i \times m_i}$$

(Eq. 9)

where,

$$i = 1,2, . . , n$$

i includes the co-products i.e., Cobalt, Copper, Nickel, Ammonium sulphate, Nickel sulphate.
n is the number of each co-product,
C_{eco} is the coefficient of economic allocation,
P_{NiSO_4} is the price of nickel sulphate,
m_{NiSO_4} is the mass of nickel sulphate,
P_i is the price of co-product i,
m_i $is\ the\ mass\ of\ the\ co-product$ $_i$

The coefficient of economic allocation is then multiplied by the inputs, outputs, and energy values of the system to achieve an inventory that is only associated with nickel sulphate.

4.2.2 Parametric Model:

There are various parameters that have an influence on energy and emission intensity of nickel sulphate production. In this study ore grade, mine type, electricity mix, nickel recovery from beneficiation, nickel recovery from primary extraction and nickel recovery from refining of nickel sulphate. In addition, the allocation type is also set as a parameter to see how the different allocation types affect the results. An overview of the how the inventory is formed can be seen in Figure 6.

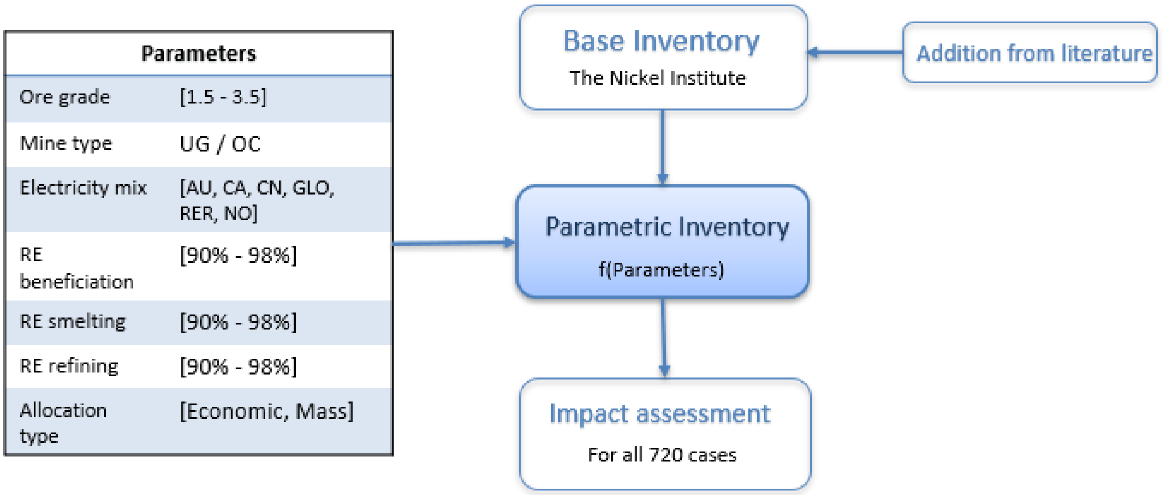

Figure 6. Parametric Inventory development

- <u>Mine-type:</u>

Both mine types, **Open-cast, and Underground mines** influence the use of power sources in different ways. Open-cast mining is usually done for laterite ores which are less energy intensive and underground mining is commonly done for sulphide ores. This parameter also affects the flows in the background system such as different amount of diesel and electricity is required based on the type of mine from where the ore is extracted. These amounts are obtained from the literature for each type.

The diesel and electricity values present in the data from Nickel Institute (Gediga and Boonzaier, 2020) did not consist of separate values for underground and open cast mines. However, (Eckelman, 2010) contained data for diesel and electricity used in underground and open cast mines for per kg nickel produced for mining and beneficiation combined. For this study, data for diesel and electricity was divided for the processes of mining and beneficiation according to their ratios from the Nickel Institute data and converted in the units of per kg nickel sulphate. Table 3 shows the energy consumption values for underground and open cast mines from mining and beneficiation.

Beneficiation is relevant here as the type of ore extracted from different mine types affects the energy use in beneficiation. The energy values that are relevant to the scenario are used in each case.

Table 3. Energy consumption values for underground and open cast mining

(Eckelman, 2010)

		Underground		**Open cast**	
		Electricity	**Diesel**	**Electricity**	**Diesel**
(Gediga and Boonzaier, 2020)	**Mining**	1.21E-01	2.44E-01	9.00E-02	5.22E-01
	Beneficiation	2.45E-01	4.99E-03	1.83E-01	1.07E-02

In addition, the infrastructure of mine is also a function of mine type and were obtained from the literature for both mine-types.

- Ore grade:

Ore grade is a way to measure the quality of ore by the concentration/percentage of the required metal in the ore. The higher the grade, the lower the energy is required to process it. The changes in ore grade are analysed in this study between the range of **1.5 and 3.5.** The ore grade specifically influences the energy used which are the flows in the background processes. In this case ore grade affects the diesel and electricity consumption for two processes i.e., ore mining and concentrate production/ ore preparation.

Since both mine-type and ore grade affect the diesel and electricity value in ore mining and beneficiation, the formula for calculation of these energy value will be incorporate both the parameters. The values for diesel and electricity for the process of mining and concentrate production/ ore preparation needs to be calculated with respect to the change in the ore grade.

If x is the ore grade, y is the mine-type and D is the theoretical diesel required by the process, then the formula for Dx which is the diesel required for ore-grade x is:

$$D = f(x, y)$$

$$D_x = \frac{D_y}{x}$$

(Eq. 10)

Similarly, E is the theoretical electricity required by the process and Ex is the electricity required by ore-grade x:

$$E = f(x, y)$$

$$E_x = \frac{E_y}{x}$$

(Eq. 11)

Here,

x= [1.5 - 3.5]

y= [underground, open cast]

These formulas are used for both the mining and beneficiation stages.

- Electricity mix:

Electricity mix refers to the combination of different sources of electricity that make up the total requirement for a country. Electricity mix varies between the countries and so does the emissions from production. Some electricity mixes include use of more fossil fuels while few have mix that are dominated by renewable energy. In this study, the electricity mix that are considered include **Global (GLO), China (CN), Australia (AU), Europe (RER), and Norway (NO)**. Ecoinvent with the help of activity browser was used to short list these areas in a way that so different regions that produce nickel sulphate and with different electricity mixes are selected. China is selected as it one of the largest producers of nickel contributing to around 31% of total production. Canada and Australia are also large producers of Nickel. Global mix is used as it gives us an average case for the production all over the world, while Europe is chosen to see how the impacts are influences if the production is in Europe. And lastly, Norway is chosen as battery production is being done in Norway at a large scale and is expected to increase many folds. There are nickel smelting plants in Norway, so it is helpful to see how different the impacts are if production is in Norway. The share of different sources of energy for producing electricity between 2018-2020 are presented for the cases under study in Table 4.

Table 4. Electricity mix for China, Australia, Global, Europe and Norway

Country	Coal	Natural gas	Renewable energy	Oil	Nuclear	References
China	69%	3%	23%	-	5%	(*Electricity mix in China, 2020 - IEA*)
Australia	56%	21%	19%	2%	-	(*Electricity generation | energy.gov.au*)
Global	37%	23%	27%	-	10%	(*Global electricity generation mix, 2010-2020 - IEA*)
Europe	12%	20%	41%	-	26%	(*Electricity mix in the European Union, 2020 IEA*)
Norway	-	-	97.5%	2.5%	-	(*Norway - Countries & Regions - IEA*)

The higher the amount of renewable energy sources used to produce the output, the lower the emissions are.

During the LCA, specific Ecoinvent identity numbers are used for each electricity mix for all the processes i.e., mining, beneficiation, primary extraction, and refining. Each electricity mix is studied in connection with other parameters.

- Recovery efficiency from beneficiation:

Recovery efficiency here refers to how effectively nickel is recovered from beneficiation process. The higher the recovery, the lower the wastage of nickel. Recovery efficiency for this parameter is chosen to be within the range of **90%** and **98%.** This parameter influences the value of concentrate that is recovered. This is a process in the foreground system. The recovery efficiency from beneficiation is calculating by dividing the amount of concentrate that is produced by the percentage that is recovered. So, if the efficiency is low, more input will be required to produce the same amount of output.

$$O_c = \frac{C}{R_c}$$

(Eq. 12)

where,

O_c is the quantity of ores required to produce an amount of concentrate to produce 1 kg of nickel sulphate.

C is the theoretical quantity of concentrate produced.

R_c is the Recovery efficiency of beneficiation.

- Recovery efficiency from primary extraction:

Similarly, recovery percentages from primary extraction are chosen to be between the range of **90%** and **98%.** This parameter is also in a foreground process in the A_{ff} matrix. The output from beneficiation is concentrate and from primary extraction is matte. Some nickel is lost while producing concentrate, and then some is lost during the production of matte. The concentrate needed to produce 1 functional unit of nickel sulphate can be calculated as:

$$C_m = \frac{M}{R_m}$$

(Eq. 13)

Where,

C_m is the quantity of concentrate required to produce an amount of matte which is required to produce 1 kg of nickel sulphate.

M is the theoretical quantity matte produced.

R_m is the Recovery efficiency of Smelting.

- Recovery efficiency from refining:

The recovery efficiency from refining that produces nickel sulphate is accessed between the range **90% to 98%** according to the model. Since nickel sulphate is the final output so this parameter affects the y-vector which is the external demand vector. The formula can be:

$$M_n = \frac{NiSO_4}{R_n}$$

(Eq. 14)

Where,

M_n is the quantity of nickel matte required to produce 1 kg of nickel sulphate,

$NiSO_4$ is the final output i.e. nickel sulphate,

R_n is the Recovery efficiency of refining process that produces nickel sulphate.

- Allocation type:

Mass allocation and **economic allocation** are used as the components of the parameter ‘Allocation type’ in this study as parameters. Both types of the allocations affect the result to a great extent. The mass allocation is used when the co-products/ by-products are all of the same category or importance while economic allocation is required when the outputs have a major difference in value. In this study both the allocation types were used to see how this impacts the assessment. This parameter is applied to the whole inventory. The coefficient of allocation was multiplied by the whole inventory for each allocation type, hence, providing two different inventories with all the dynamic parameters discussed above are also applied on the inventories.

4.2.3 Parametric LCA:

Parametric Model in LCA helps to generate multiple inventories, with each having a different combination of the parameters that are the subject of the study. For Parameterization, MS Excel is used. In one sheet, inventory is built. In the ‘Inventory’ sheet a table with columns showing all the inputs to each process and the rows consisting of all the processes, is made, and filled all the corresponding values. A similar matrix for stressors is made. For each input to the processes in the inventory that is influenced by one or more parameters, is developed, and added in the corresponding cells. Another sheet is made where the dynamic parameters that are subject to change are entered with their values or inputs. The cells containing the values for the parameters are linked to the formulas for the inputs that are influenced by those particular parameters, in the ‘Inventory’ sheet in way that if a value is altered in the parameters page, it is automatically changed in the formula of inputs in the inventory sheet.

Python is used to generate all the possible scenarios with combinations of each parameter. In this study, 720 cases were generated with the combination of the selected parameters. With these cases a total of 720 inventories were generated each having a different set of parameter values. These inventories were then used to carry out the assessment.

4.3 Impact Assessment:

For each of the 720 inventories generated by varying the parameters between their ranges, we now proceed to carry out impact assessment for each of these inventories to generate 720 LCA cases as results. For the impact assessment a software called Arda is used, which is developed by Industrial Ecology program at the Norwegian University of Science and Technology (NTNU). This software is assisted by MATLAB for performing LCA. The software is developed based on Ecoinvent database and uses the ReCiPe framework to carry out the assessment. In addition, Python was also used to aid the assessment.

A template for Arda is available in Microsoft Excel that treats the data in a way that is readable for MATLAB. Arda template has three main sheets that require data input for LCA. The sheet 'Foreground' consists of the y-vector for functional unit and the A_{ff} for the foreground process data of the requirement matrix with their Arda IDs starting from 10000001 are given to them. Second sheet 'A_bf' consists of the inputs from background to foreground where the background process IDs from Ecoinvent are linked to their respective foreground process ID. In this way the inputs from background are allocated to each of the process in the foreground. The third sheet 'F_f' is for the direct stressor emissions from the foreground processes. Here also the stressors and their Ecoinvent IDs are linked to the foreground process Arda ID. The template is filled according to the LCI data and is ran in MATLAB through an ARDA interface. The results are generated as an Excel file.

For parameterization, the excel file made for parametric model is added to Arda template as an extension including the "Inventory" and "Parameters" sheets. From the

‘Inventory’ sheet, all the values of inputs to the processes are linked to the ‘Foreground’, ‘A_bf’ and ‘F_f’ sheets.

The model works in such a way that MATLAB runs all the 720 inventories that were generated and produces result in the form of 720 excel files for each of the case.

4.4 Interpretation

This is the last step of LCA where the results are analysed and presented using figures. In this study, Python was used to extract all the results from each scenario and to illustrate the results. The information generated in the form of numerical data in excel files is extracted with the help of Python. Python reads the data from all the 720 files and present it in the form of data frame. This data frame is then used to present the data in the form of figures. In this study the impact being studied is the Global warming potential of nickel sulphate. The relation of the parameters to the Global Warming Potential of producing nickel sulphate is analysed in more detail in the results section.

5 Results:

In this section, the impacts from the production of nickel sulphate will be studied. The primary focus nevertheless is on the climate change potential. The change in impact potential of nickel sulphate production as a result of change in the parameters is analysed. This helps to study the influence of the parameters on the global warming potential (GWP) of nickel sulphate.

5.1 Midpoint Impact categories:

Midpoint approach looks at the impacts in the middle of the cause-and-effect chain. ReCiPe method is used for the LCIA calculation which describes different emissions in terms of impact scores with the help of characterization factors. The share of each stage of nickel sulphate production in midpoint impacts is presented in Figure 7. Most of the impact categories are dominated by the impacts from the nickel matte and nickel concentrate production.

Some of the important environmental impacts include fossil depletion, human toxicity, land use change, particulate matter formation, freshwater ecotoxicity and climate change. Fossil depletion occurs as a result of excessive use of fossil fuels. Human toxicity is caused by intaking harmful substances such as mercury, arsenic and copper that are emitted during the production. Freshwater ecotoxicity occurs when fresh water is taken from the environment, used, and released into the environment with toxic substances. similarly other impacts are also very harmful for the environment.

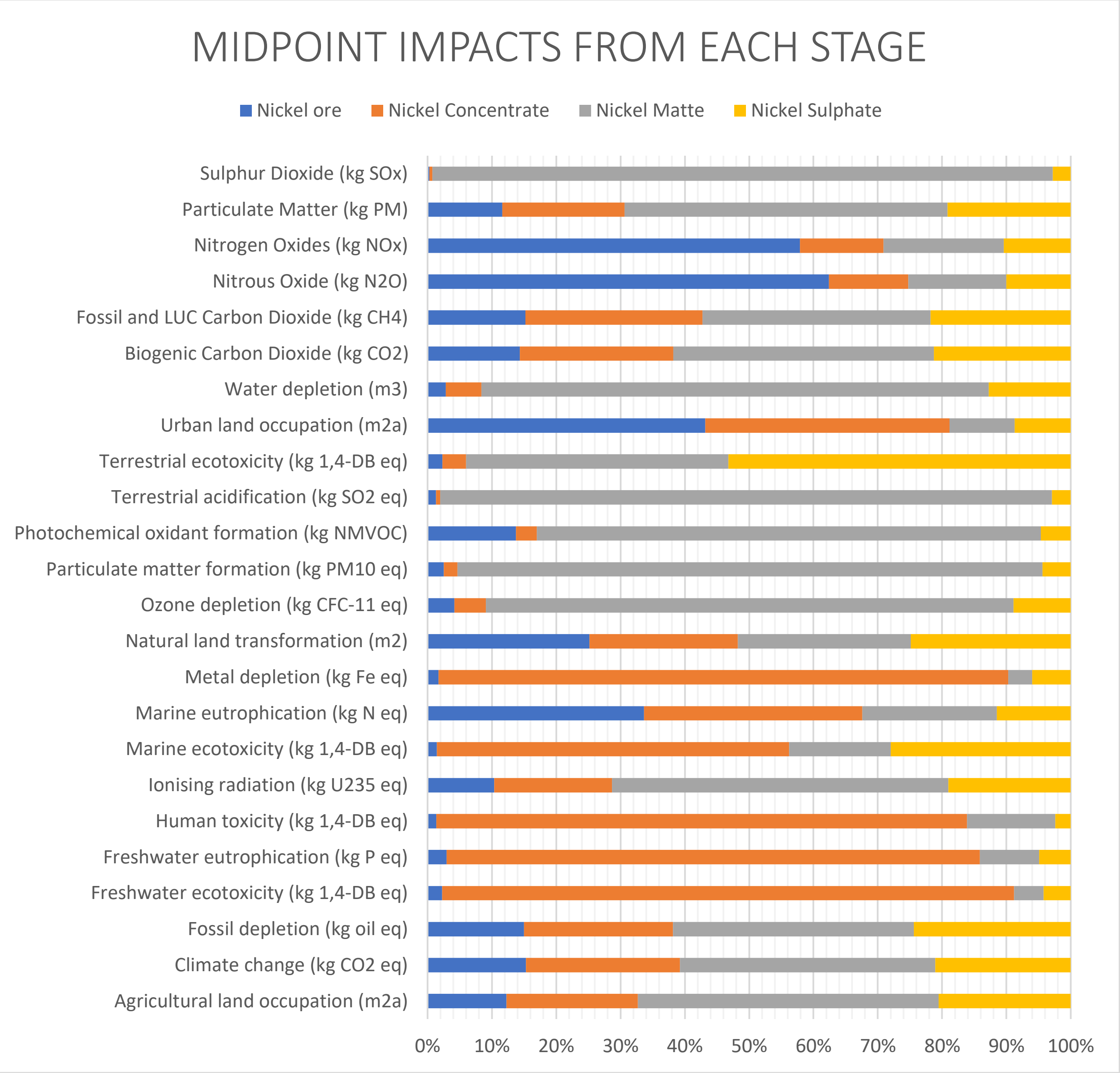

Figure 7. Share of Nickel Sulphate production stages in the Impacts at the Midpoint level

5.2 Global Warming Potential of Nickel Sulphate:

Global warming refers to the phenomenon of warming up of earth’s temperature in long term as compared to the pre-industrial level. This global warming is due to the greenhouse effect as a result of excessive emissions of carbon dioxide, methane, Chlorofluorocarbons (CFCs), and nitrous oxides. These gases trap the infrared radiation from the sun in earth’s atmosphere making it warmer. Over time, it results in climate change which further causes many problems such as melting of arctic ice sheets, sea level rise, ocean acidification, changes in precipitation droughts, intense storms, species extinction, and many more. Global warming potential (GWP) is the potential of an anthropogenic activity to contribute to the global warming. It is quantified in terms of CO_2-eq.

The intensity of GWP of nickel sulphate produced from primary route depends on the ore grade, mine-type, transport distances, and energy mix. In figure 8, a box plot displaying the total GWP of Nickel sulphate production from cradle to gate is presented.

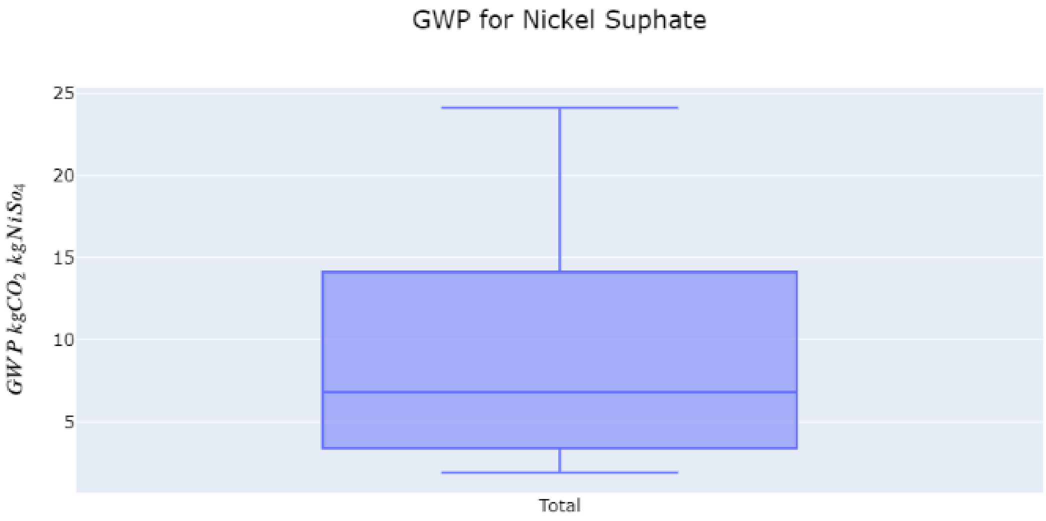

Figure 8. Global Warming Potential of Nickel Sulphate.

The mean GWP from all scenarios for producing 1 kg Nickel sulphate is around 6.8 kg CO_2-eq., the first quartile is around 3.4 kg CO_2-eq., and the third quartile is 14.1 kg CO_2-eq.

A process-by-process division of the GWP is presented in Figure 9. The mean GWP from all the scenarios is represented by the horizontal line inside the box.

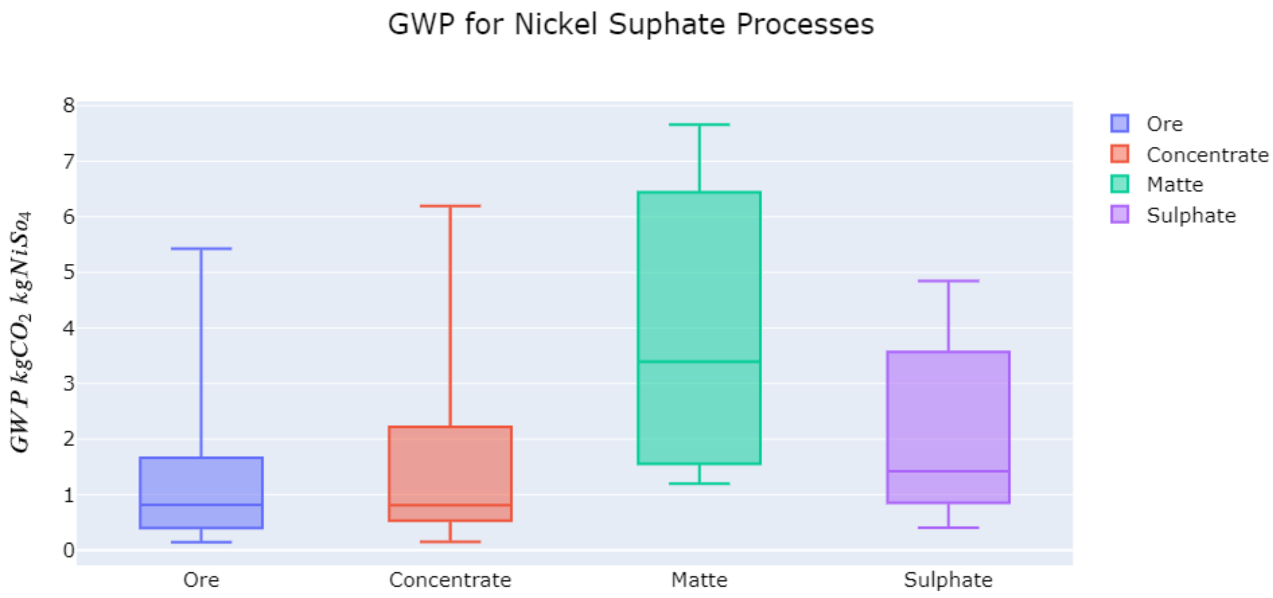

Figure 9. GWP of Nickel sulphate production processes

For mining the mean is around 0.81 kg CO_2-eq., for concentrate it is 0.81 kg CO_2-eq., for primary extraction 3.4 kg CO_2-eq., and 1.42 kg CO_2-eq. for refining to produce nickel sulphate. The nickel matte production done by the primary extraction process contributes the most to the total emissions from the nickel sulphate production. According to the mean of all cases primary extraction contributes around 49.9% of the total GWP of nickel sulphate production. The second most emission intensive process is the refining that produces around 20.9% of the total CO_2-eq emissions.

In these box plot, the height of the box represents the difference between the first and third quartile. The area between these quartiles shows the spread of the values above and below the mean. In all four stages most of the scenarios represent the values above the mean however, in primary extraction (matte production) the spread of values below the mean is more than the other stages. This mean that the emission variation in all stages is mostly above the mean but in primary extraction the chances of emissions being below the mean are also higher. The values of these quartiles are presented in Table 5.

Table 5. First and third quartile for GWP of all stages of nickel sulphate production

Stages	*1st* quartile	*3rd* quartile
Mining	0.39 CO_2-eq	1.66 CO_2-eq
Beneficiation	0.53 CO_2-eq	2.23 CO_2-eq
Primary extraction	1.55 CO_2-eq	6.44 CO_2-eq
Refining	0.85 CO_2-eq	3.57 CO_2-eq

The bars above and below the box shows the maximum and minimum ranges in which the emissions can fall depending on the different scenarios.

A scenario with a combination of parametric values such as lower ore grade of nickel, an electricity mix dominated by fossil fuel consumption and low recovery ratios will produce much high emissions as compared to other cases. The relation between different parameters and their influence on different stages are presented.

5.3 Influence of ore grade:

Ore grade has a great influence on the GWP of mining and concentrate production, if the ore grade is lower more mining has to be done to produce the same amount of nickel produced by higher ore grade. More energy is also required to extract the nickel from ore and to produce nickel concentrate. Figure 10 shows the line graph of how change in ore grade changes the GWP of producing 1 kg nickel sulphate for different electricity mixes.

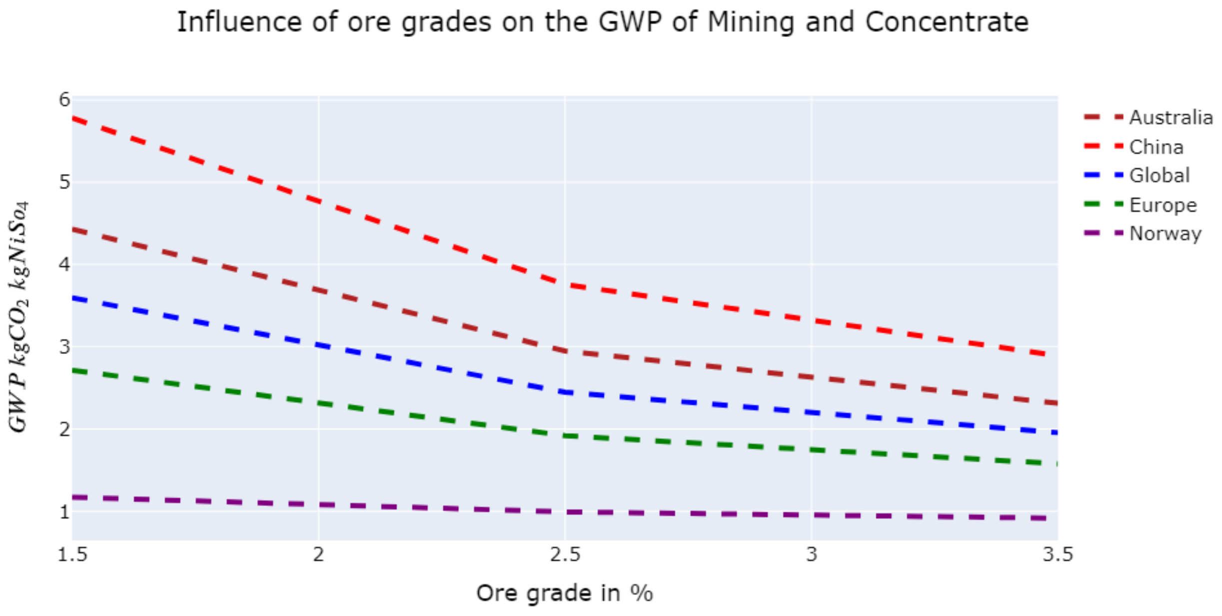

Figure 10. Influence of Ore grade of mining and concentrate production for different electricity mixes.

Here the ore grade on the x-axis is within the range of 1.5 to 3.5. On y-axis, the GWP in terms of carbon dioxide equivalent per kg nickel sulphate production, for the sum of mining and concentrate is presented. The relation between the ore grade and the emissions is depicted for the 5 regional cases that are selected. The electricity mix for Australia, China, Global, Europe, and Norway are presented in connection with the change in ore grade. The mix having larger share of non-renewable resources such as China and Australia, have higher emissions and the mix dominated by renewable energy such as Europe and Norway have lowest emissions. However, the case of global production is treated as the average of all the production in the world to compare other cases' effectiveness. Table 4 shows the share of energy sources for each case.

Most of the curves have a kink at ore grade 2.5, in economics terms this means that the curve before this point is elastic while after this point the curve is more inelastic. An explanation to this can be that a small change in ore grade before 2.5 causes a large change in the emissions. However, after the ore grade 2.5, a small change in the ore grade does not causes a large change in the emissions. From this we can say that as the ore grade decreases, there is a gradual increase in the GWP and the ore grade 2.5 is the point after which the emission intensity increases. Slope of both the lines is calculated by:

$$\text{Slope} = \frac{\Delta y}{\Delta x}$$

The slopes before and after the ore grade 2.5 are:

Table 6. Slopes of the ore grade curves before and after the ore grade 2.5

Mix	**Before 2.5**	**After 2.5**
CN	-2.02	-0.87
AU	-1.48	-0.64
GLO	-1.15	-0.49
RER	-0.80	-0.34
NO	-0.18	-0.08

It can also be noted from the graph that as the ratio of renewable energy sources increases in the electricity mix, the curve becomes slightly flatter as compared to the mix with higher share of non-renewable energy sources. A reason for this can be that as the cleaner source of energy is used, the impact of the ore grade on the emission intensity of mining and concentration decreases.

5.4 Influence of Mine-type:

The type of the mine from where the ore has been extracted also contributes to the emission intensity of production of nickel sulphate. The stages it affects are the ore mining and the concentrate production. The two types of mines are open-cast and underground. Both the mines have different characteristics and requirements. As mentioned in section 4.2.2, open cast mines have higher requirement for liquid fuel while underground mines require more electricity. Figure 11 shows the relation mine type with recovery from beneficiation with respect to the GWP in terms of carbon dioxide equivalent per kg nickel sulphate production.

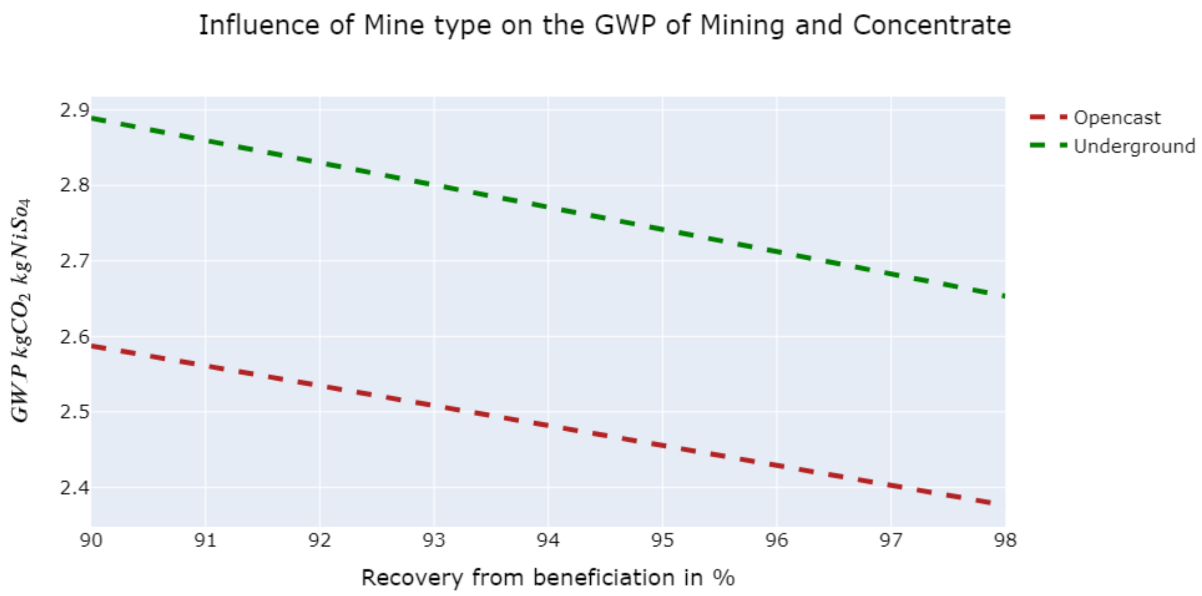

Figure 11. Influence of Mine-type on mining and concentrate production.

The x-axis shows the recovery efficiency of beneficiation process ranging between 90% to 98%. This means that if ores containing 1 kg of nickel are sent for beneficiation, and if the recovery rate is 90% then concentrate containing only 0.9 kg of nickel is recovered. Y-axis shows the GWP of producing 1 kg nickel sulphate. We can see that with minimum recovery ratio in this study, i.e., 90%, underground mining produces around 2.9 kg CO_2-eq emissions for mining ore and producing concentrate while open-cast mining produces around 2.6 CO_2-eq emissions. While on the other hand, with maximum recovery rate i.e., 98%, underground produces 2.7 CO_2-eq and open-cast produces 2.4 CO_2-eq.

The reason for higher emissions from underground mines could be that these mines require a lot of energy as the mining takes place deep down in the earth. Reaching to the ores needs a lot of effort in drilling, in transporting equipment underground, removing water and bringing the ore on the ground. In addition, excessive ventilation is required in the underground mines.

As the recovery rate increases, on the x-axis, the emissions decrease for both the mine-types. We can see a linear trend. The emissions difference between both the mine types shows a very small change due to the change in efficiency of recovery.

The slope of line for both the mines are:

Table 7. Slopes for the curves for open and underground mines

Mine type	Slope
Open cast	-0.028
Underground	-0.031

The negative sign represents the direction of the slope i.e., negative showing the negative relation between both the variables on the axis.

The difference in the slopes show that the lines are not parallel. Both the lines have a negative slope but the line for underground mining is steeper. This could mean that increasing the efficiency of recovery have a higher effect on underground mining than on the opencast however the difference is minor. Both the mine types show a decrease in emissions as a result of increase in efficiency.

5.5 Recovery from Beneficiation:

Recovery from beneficiation is the result of concentrate production from sulphide ores and ore preparation for laterite ores. The relation of beneficiation recovery efficiency in percentage with the GWP from mining and concentrate production for all the electricity mix cases is shown in Figure 12.

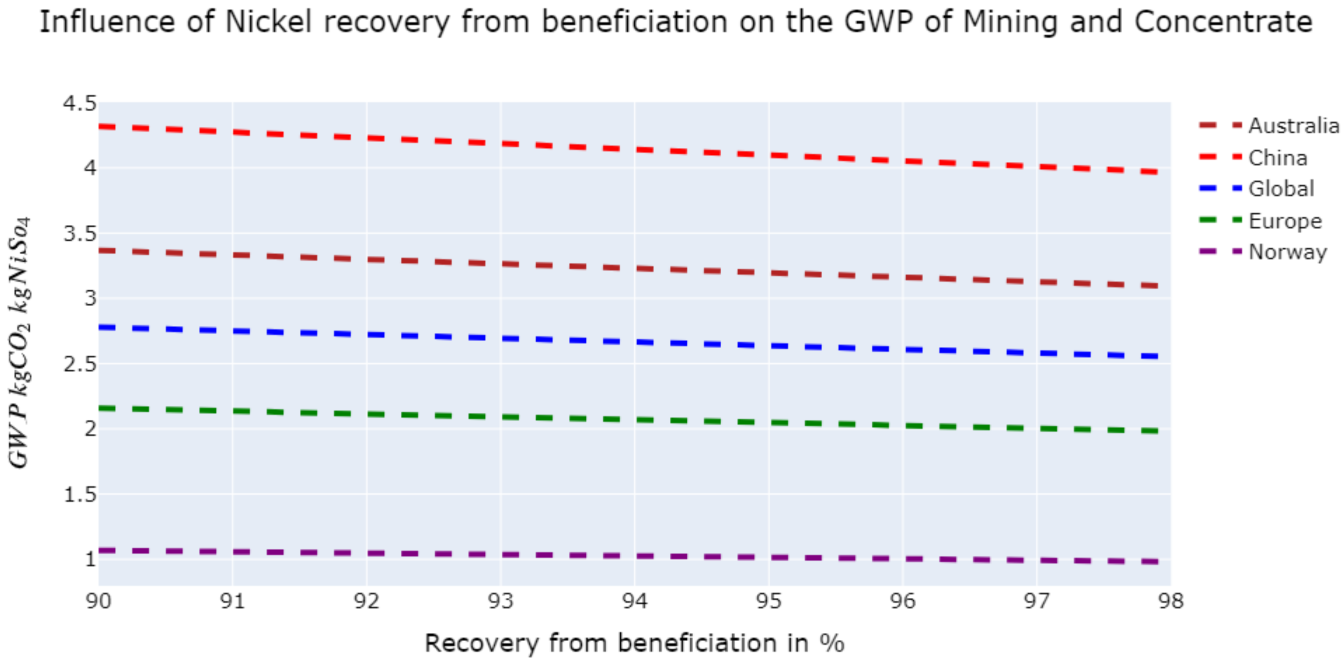

Figure 12. Influence of Beneficiation Recovery Efficiency from mining and concentrate production,

The x-axis shows the recovery efficiency of beneficiation process ranging between 90% to 98% while the y-axis shows the GWP of producing 1 kg nickel sulphate. From the cases under study, the highest emissions are from Chinese mix, followed by Australia as these mixes are dominated by the use of fossil fuels. Both these mixes are above the global emission level. Europe and Norway have emissions below the global level which is the average. Norway's emissions are the lowest as compared to any other case by a great difference. This is because the Norway's mix consists of only 2.5% share of non-renewable energy sources. However, the change in emission intensity or the GWP of mining and beneficiation due to the change in the recovery efficiency for different electricity mixes is quite low. Having high recovery efficiency does decrease the GWP but with a vey small change. The slopes for all the curves of electricity mixes showing the influence of recovery efficiency of beneficiation on the emissions of mining and concentrate are:

Table 8. Slopes for beneficiation recovery efficiency curves for mining and concentrate.

Mix	Slope
CN	-0.044
AU	-0.034
GLO	-0.028
RER	-0.022
NO	-0.011

From the slopes (Table 8), we can see that the difference in the slopes is very small but the slope for China is the steepest, followed by Australia, then global case. The slope for Europe is flatter than global case and for Norway it is the flattest. From this we can conclude that the cases with high GWP have higher potential to decrease their emissions with an increase in the recovery efficiency.

In the above case we have focused on both mining and concentrate production. However, if we focus only on the beneficiation recovery efficiency from concentrate production process then the relation is shown in Figure 13.

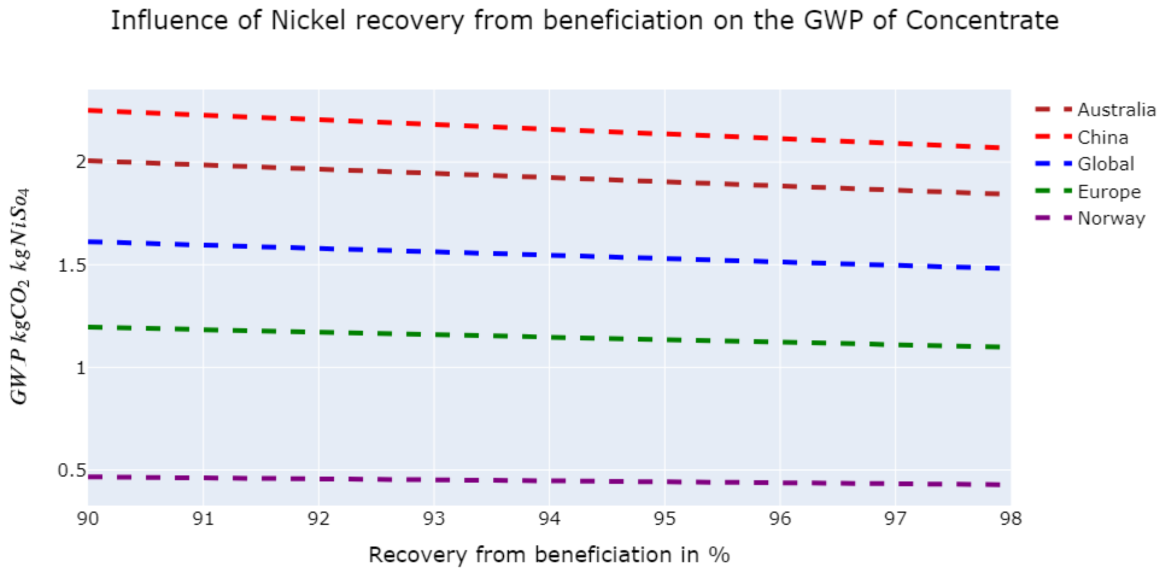

Figure 13. Beneficiation Recovery Efficiency from concentrate production.

Here it can be seen that the GWP of China curve decreased and the difference between Australia and China is smaller now. This could mean that the mining of ore in China has a significant effect on the GWP. The slopes of the curves have also changed and are flatter now (Table 9).

Table 9. Slopes for beneficiation recovery efficiency curves for concentrate.

Mix	Slope
CN	-0.023
AU	-0.020
GLO	-0.016
RER	-0.012
NO	-0.005

This confirms that reducing the share of non-renewable resources from the electricity mix in both mining and beneficiation can reduce the GWP to a larger extent.

5.6 Recovery from Primary Extraction:

Nickel concentrate produced from beneficiation then enters the process of primary extraction where it is converted into nickel matte through smelting or sulphidation. The recovery efficiency of primary extraction process to produce nickel sulphate determines the GWP of this process. The relation between the recovery efficiency from primary extraction to the GWP of the process is shown in Figure 14.

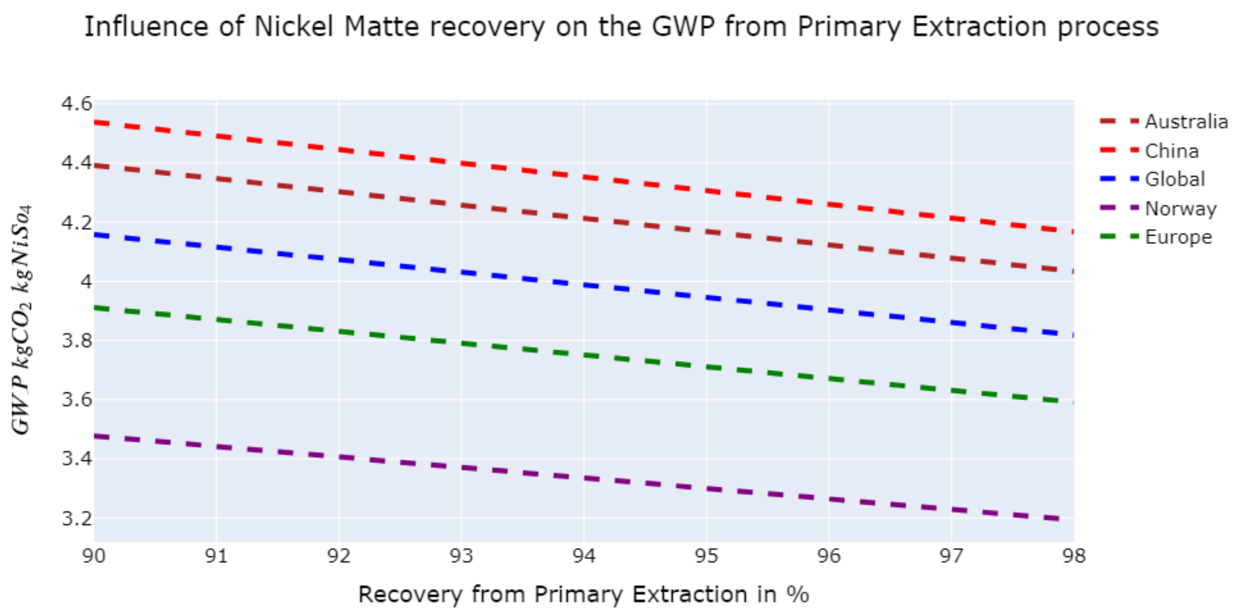

Figure 14. Influence of Nickel Matte recovery on GWP of Primary extraction.

The x-axis shows the recovery efficiency of primary extraction process ranging between 90% to 98%. This means that if nickel concentrate required to produce1 kg of nickel is sent for primary extraction, and if the recovery rate is 90% then matte containing only 0.9 kg of nickel is recovered. Hence, more nickel concentrate is required such that 1 kg nickel is produced even after the wastage of 10% nickel.

Y-axis shows the GWP of producing 1 kg nickel sulphate. As the recovery efficiency increases for producing nickel matte, the GWP decreases in a linear manner. The slopes of the curves are steeper than the curves of the Concentrate recovery efficiency curves. The slopes of these curves are:

Table 10. Slopes of primary extraction recovery curves.

Mix	Slope
CN	-0.046
AU	-0.045
GLO	-0.042
RER	-0.040
NO	-0.035

Steeper curves show that a small increase in the recovery efficiency causes bigger decrease in the GWP of the process.

5.7 Recovery from Refining:

Refining is the final process in the production of nickel sulphate according to this study. Refining is done by either leaching or electrowinning processes. The relation between the GWP of producing nickel sulphate from nickel matte with the recovery efficiency of the process is shown in Figure 15.

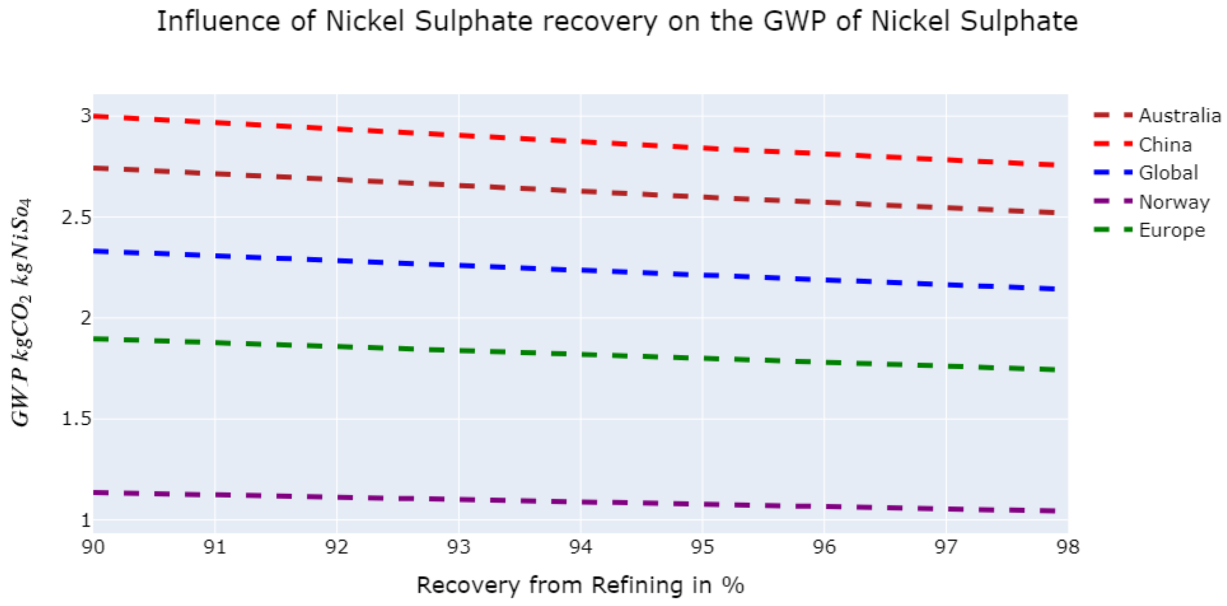

Figure 15. Influence of Nickel sulphate recovery efficiency on the GWP of Refining process

On the x-axis, recovery percentages of refining are mentioned and on the y-axis is the GWP of the refining process in terms of kg CO_2-eq. per kg nickel sulphate produced. The decrease in the GWP of producing nickel sulphate with the increase in the efficiency of refining is also linear. However, the curves are flatter than the recovery from primary extraction process. The slopes of these curves are:

Table 11. Slopes of the curves for Refining recovery efficiency.

Mix	**Slope**
CN	-0.03
AU	-0.03
GLO	-0.02
RER	-0.02
NO	-0.01

Although the lines appear to be parallel but there is a small difference in the slopes of these lines.

5.8 Allocation Type:

Another parameter that was considered in the assessment is the Allocation type. This parameter does not influence the actual GWP of the production neither change anything in the system. This parameter is only concerned with the calculation of the results. The inputs and outputs to the system are allocated among all the co-products and by-products either with regards to their mass output or with their economic value or even with a combination of both types of allocations. Selecting the allocation type can have a great effect on the results and can lead to either over-estimation or under-estimation of the impacts. Two types of allocations were performed in this study. Figure 16

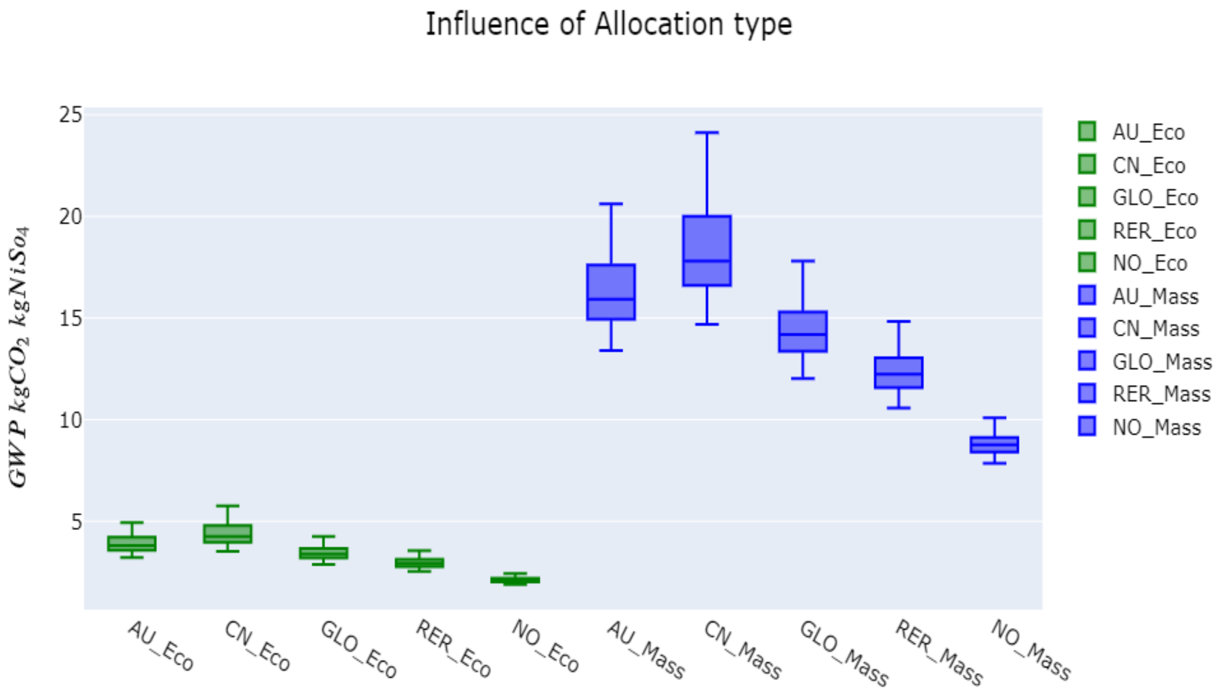

Figure 16. Influence of Allocation types.

The x-axis shows all the electricity mixes for both economic and mass allocation while the y-axis shows the GWP of producing 1 kg nickel sulphate. The mass of Nickel sulphate is higher than the mass of other co-products so more impacts are attributed to nickel sulphate but since the economic value of nickel is low as compared to other co-products so less emissions are associated with nickel sulphate. Hence, the results for economic allocation of nickel sulphate are much lower than the results for mass allocation.

This influence of allocation type is also presented through Figure 17 and 18.

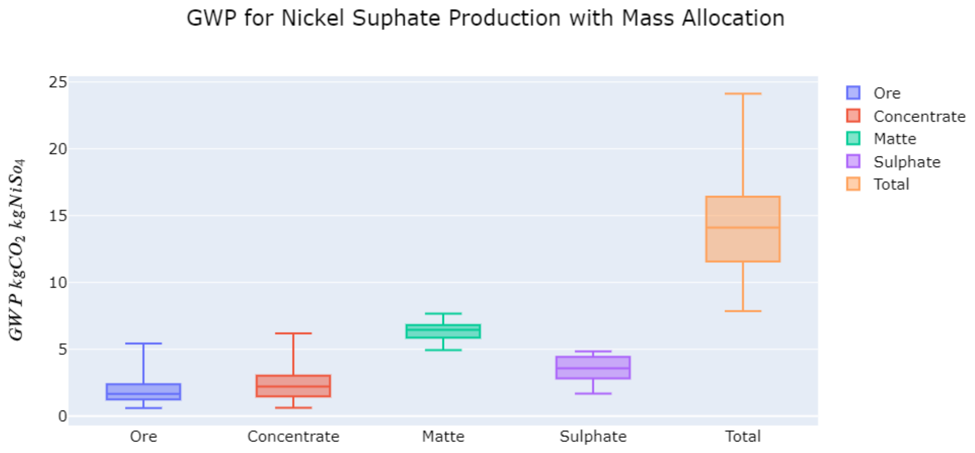

Figure 17. GWP of all stages with Mass allocation.

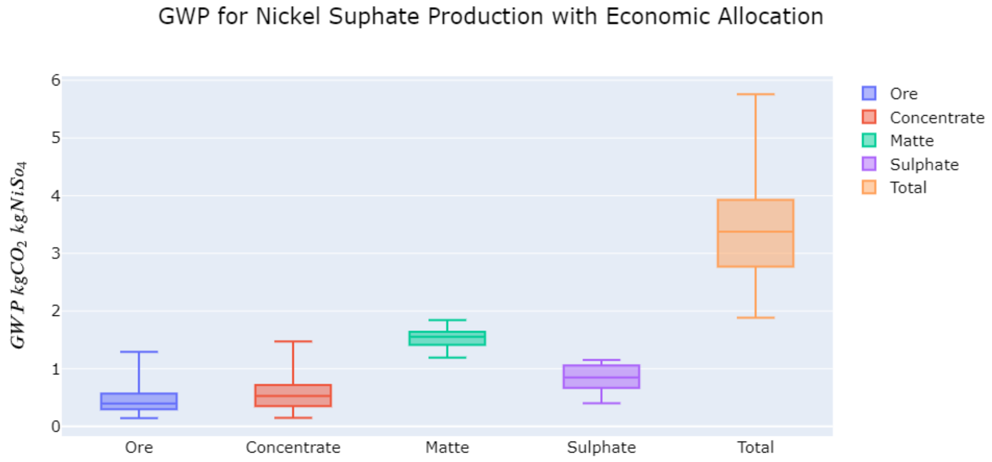

Figure 18. GWP of all stages with Economic allocation

Here at different stages of nickel sulphate production, the magnitude of emissions differs on the bases of type of allocation selected. Mass allocation has magnified the results as the total emissions from nickel sulphate production with mass allocation is within the range of 7.9 to 24.1 kg CO_2 eq. per kg nickel sulphate produced. While for economic allocation it is within the range of 1.9 to 5.8 kg CO_2-eq. per kg nickel sulphate produced.

6 Discussion:

In the modern times the requirements of society have shifted to increased use of technologies. These technologies require an energy source which in most cases is batteries. Battery development has made incredible improvements in past years. Experiments with new materials, chemistries and proportions of these materials have made a great difference. These improvements made possible the long life as well as more battery capacities and allowed us to move from powering small devices to powering cars and eventually houses. The performance of these batteries has also improved along the way, and it is expected that these batteries will help decrease the environmental impacts of traffic. Lithium-ion batteries have high energy and power density, high efficiency, lighter weight, and a long life. However, battery technology needs to be constantly studied so that a good battery management system is developed to meet the demands of more revolutionized electric cars. Battery safety and battery life are of great concern as longer life of battery can ensure lower life-time emissions.

In future it can be expected that sustainably produced energy stored in LIBs become the main source of power for the appliances and other technologies. In this case the most pressing issue becomes the sustainable production of these batteries. The materials used in batteries mostly go through an intensive production process before they are used in the batteries. Most of the metals are mined, concentrated, smelted, and refined after which they can be used in the batteries. According to Dunn *et al.*, (2015) the battery assembly emissions are too high that the difference in emissions from primary and secondary materials become too small.

In order to reduce the emission intensity of battery production, it is very important to study what components play a substantial role in emission intensity of battery production. Nickel sulphate is one of the nickel products which is an input to battery production and plays a major role in battery's operations. Its unmatched characteristics make it a decent choice for use in batteries. In addition it's use in batteries can actually help to reduce the use phase emissions of batteries (Mistry *et al.*, 2016). Increase in the battery nickel content is expected to increase while the content of cobalt to decrease to increase the energy density (Emilsson and Dahllöf, 2019). However, nickel production also has higher emission intensity as compared to other materials used in the batteries (Schmidt *et al.*, 2016).

6.1 Goal revisited:

The goal of this study was to investigate the process within the value chain that has the most influence on the emission intensity of primary nickel production. The second goal was to study the parameters that have an influence on the Global Warming Potential of Nickel sulphate and to see how changing them can impact the emission intensity of nickel production with respect to different electricity mixes. In addition, the influence of allocation type on the results was also to be studied.

6.2 Methodology evaluation:

The methodological approach used in the assessment is a combination of Lifecycle assessment (LCA) with the Parameterization. LCA is a well-established approach for calculating the impacts of a product over its lifecycle. However, a combination of Parameterization with LCA is quite infrequent and no standardized approach is established for this kind of assessment. The approach used in this paper aims to vary the value of each parameter to see how it influences the results. This is done by keeping five parameters free and fixing the rest of the inventory. Then different scenarios are formed based on the combinations of these parameters to find out the influence of these free parameter.

Allocation is performed on the inventory data before the assessment as the system boundaries of nickel sulphate production includes the data for the production of co-products. As the base inventory is from the Nickel institute for the production of nickel sulphate, the Nickel institute has also performed a combination of both economic and mass allocation on the data. However, the method for performing allocation is not described in detail so it is unclear from the NI report that which allocation is dominant and what stages the allocation has been performed on. For this study, to see how it was performed in the Nickel Institute's (NI) report, one case was to perform allocation on the entire inventory and second was to just perform allocation on the data for producing nickel sulphate from nickel matte. The former produced the results closer to the NI's report and hence, allocation on the entire inventory was performed.

6.3 Results quality assessment:

Since the LCA of nickel sulphate production has not been widely studied, the present studies may be insufficient. It is difficult to only have one LCA fit many uses in this case. This is because there can be various differences in the system boundaries, goal of study, methods, and interpretation of the results.

One of the goals of this study was to find out the hotspot of emissions. From the results we can see that the production stage with the highest emission intensity is the nickel matte production from primary extraction process followed by the refining process while mining and beneficiation have comparatively lower emissions. Similar results are shown in the Nickel Institute (Gediga and Boonzaier, 2020) and (Mistry *et al.*, 2016) where the emissions from primary extraction are also the highest. (Wei *et al.*, 2020) also confirms that smelting is the most energy intensive process in nickel products production.

The parameterization of ore grade shows that as the ore grade increase, the energy requirement decreases. This has been confirmed by (Eckelman, 2010) that ore grade is the major determinant of the energy use in the production of nickel sulphate and state that the energy required to treat these ores is bound to increase in future as the ore grades are falling. (Schmidt *et al.*, 2016) and (Wei *et al.*, 2020) also confirm this.

Different electricity mix have different emission intensities. (Emilsson and Dahllöf, 2019) uses different electricity mixes to study their impact on various countries for battery production. They have also studied how changing an electricity mix dominated by clean energy to a mix dominated by fossil fuels increase the emission intensity many folds.

For the mine type parameter, this study shows that the emissions from underground mining are higher than the open cast mining. This result is confirmed by (Lloyd *et al.*, 2011) which states that the more energy is required by the underground mining as a result of more drilling and transportation of equipment's and rocks to and from the mine. Underground mines require more ventilation as well.

In this study, both mass and economic allocations have been performed on the data separately. The mean of GWP for mass allocation is around 14.1 kg CO_2 eq., while for economic allocation it is around 3.4 kg CO_2 eq. The result from the Nickel Institute shows that the emissions are around 4.9 kg CO_2 eq. for the four stages included in this study. One of the reason or the difference can be the use of combination of both types of allocation as the result from the Nickel Institute (NI) is between the result from mass and economic allocation. However, the results from nickel Institute are closer to the result from economic allocation than to the mass allocation. (Ardente and Cellura, 2012) provides in depth explanation of the allocation especially economic allocation and describes scenarios to educate about the best allocation method to use in those scenarios.

However, the base inventory used in this study sourced from the Nickel Institute has provided the data as an average of both pyrometallurgical and hydrometallurgical approach for nickel sulphate production form both sulphide and laterite ores. Since both the approaches are extremely different in terms of their energy requirements, it is difficult to infer how this result can be used for the estimation of one particular type of approach or ore type. The energy intensity for nickel sulphate production in this study is higher as compared to the energy required by only pyrometallurgy approach (Wei *et al.*, 2020).

6.3.1 Implications:

- *LCA lessons:*

Lifecycle assessment is a holistic analysis of the entire lifecycle of a product. LCA can play a very important role in the improvement of a product's development and strategic planning. LCA lets the operator decide the scope of the assessment, however, more detail leads to a better assessment. LCA can be used in a variety of ways and the type of assessment that matches the requirements can be chosen.

- *Case lessons:*

The ore-types, ore grades, mine-type, mining procedure, production routes, electricity mix and locations of production of nickel sulphate also influence the energy and emission intensity of nickel sulphate production. On the other hand, methodological procedures such as goal, system boundaries, and allocation of impacts influence the calculation of the impacts. Additionally, many products of nickel are present that differ in their characteristics and nickel content. The impacts of all the nickel products also differ based on their nickel content. Where there are so many factors that influence the impacts and their assessment, it is difficult to attribute the LCA calculated impact to any specific case. This creates the need to study the change in impact intensity as a result of change in these parameters.

Another lesson is that the process that has higher emissions have higher potential to reduce these emission as compared to other processes.

6.3.2 Guidance for further work.

Even though recycling of batteries is an important study subject and is gaining more popularity but to compare the advantages of battery recycling over battery materials’ primary production, the impacts from the production of virgin materials is especially important. This aids to understand the difference by which recycling outweighs primary production (Schmidt *et al.*, 2016).

The main purpose of this study was to study the GWP from the production of nickel sulphate through parameterization. However, disaggregation of hydrometallurgical and pyrometallurgy was not possible with the data available. More concrete data, with separate processing routes is required for a robust calculation of impacts. In addition, more knowledge and specific data for different production sites is required as the location of production also has a great impact on the environmental profile of nickel sulphate.

The proportion of sulphide ores and laterite ores in the total production of nickel sulphate is changing continuously (Schmidt *et al.*, 2016) as the laterite ores are increasing. Also, the methodology for production of nickel may also have changed over time. In addition, for the future supply security or risk also needs to be determined more often. Constant research and investigation of future trend is required to strongly capture the actual impact of the production.

7 Conclusion:

The demand for batteries has been increasing and is bound to increase many folds in near future. The demand for Nickel sulphate is increasing as a result of this increase in the demand for batteries especially for the use in electric vehicles. This paper aims on studying the dynamics of the nickel sulphate production with respect to Global Warming Potential (GWP) to investigate the influence of different parameters on the energy demand and emission intensity of nickel sulphate production. A parametric model is introduced in the LCA framework that helps to generate multiple inventories. These inventories then result in multiple assessments which are then used to analyse the environmental impact of nickel sulphate from different conditions such as the ore grade, mine-type, electricity mix, efficiency recoveries from all stages as well as allocation type on the data.

The results show a negative relation between the GWP and ore grade as well as the recovery efficiencies. The higher the ore grade and recovery efficiencies are, the lower the energy is required for the process and lower emissions will be generated. Mine-types also have different energy requirements and according to the results, underground mines are more energy and emission intensive. A few different energy mixes were used to investigate the GWP of producing Nickel sulphate in different regions where the global electricity mix was taken as the average for all the mixes. According to the results China had the most emissions, followed by Australia and both are above the global level whereas Europe and Norway lie under the global emissions from Nickel Sulphate production. This is due to the higher proportion of renewable energy sources. Lastly, mass and economic allocation show two perspectives to the analysis based on the physical mass or economic value of the product.

Even though research on battery production is increasing tremendously as a result of high demand but the research on the input materials, such as nickel sulphate, is also very important for a better traceability of the environmental impact. Due to the unmatched nickel sulphate properties its proportion is increasing in the LIBs. Constant research is required for capturing the dynamic production of nickel sulphate used in the battery production.

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Appendix A: Literature

Lithium-ion battery comparison:

A brief summary of the characteristics of different Li-ion batteries is reproduced from (Saldaña *et al.*, 2019) where the characteristics are rated based on a scale from 1-3 in Figure 19.

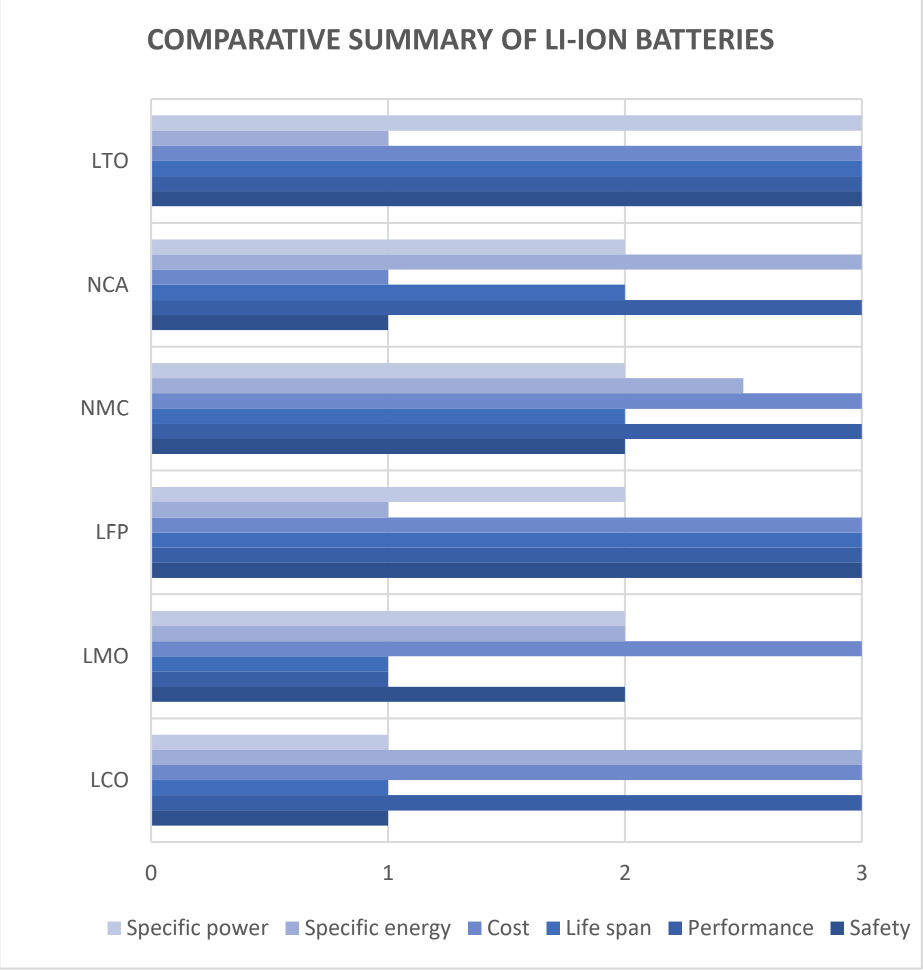


Figure 19. Comparative summary of Li-ion Batteries

Appendix B: Methodology

Allocation:

In order to find out how the allocation was performed; two alternative approaches were used:

1. Cradle to gate data was allocated to Nickel sulphate. This means that all the inputs and outputs from mining to refining were subject to mass and economic allocation.
2. Only the data for producing nickel sulphate from nickel matte was subject to mass and economic allocation while the data for other processes was kept the same.

The performed allocations provided four types of data sets: Economic allocation on cradle to gate data, economic allocation only on nickel sulphate production from matte, Mass allocation on cradle to gate data, and mass allocation only on nickel sulphate production from matte. LCA was performed on each of four data set to get the similar results as the results of the Nickel Institute. Table 12 and 13 show the ratios used to allocate inputs to nickel sulphate for both mass and economic allocation.

Table 12. Ratio of co-products of nickel sulphate and co-products for Mass allocation.

Mass Allocation

Outputs	**Mass (kg)**	**Ratio**
Cobalt	0.04	0.01
Copper	0.71	0.15
Nickel	2.0	0.43
Ammonium sulphate	0.89	0.19
Nickel Sulphate	1.0	**0.22**
Sum	**4.64**	**1.0**

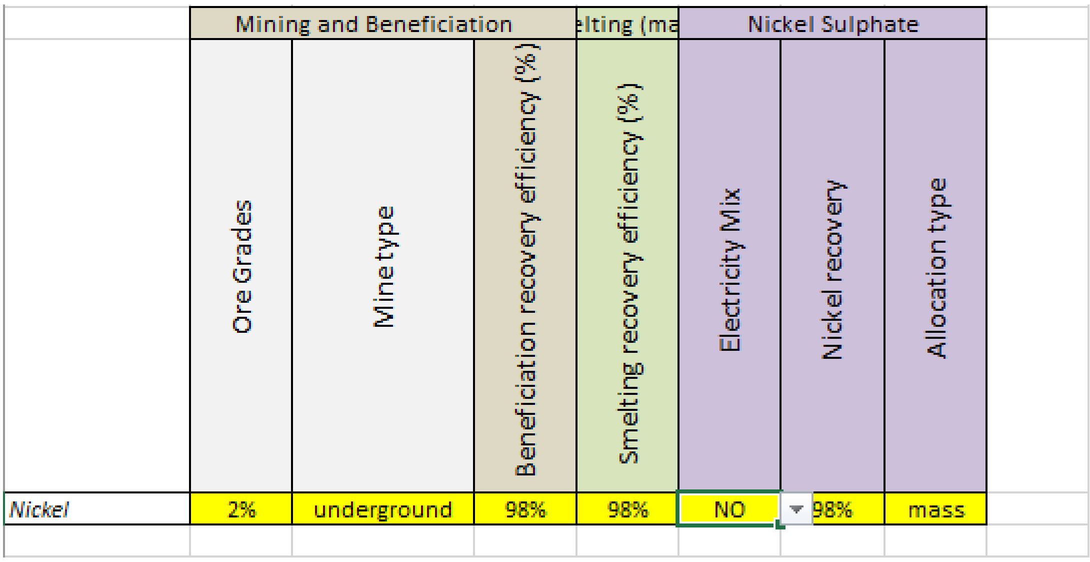
Table 13. Ratios of nickel sulphate and co-products for Economic allocation

Economic Allocation

Output	**Price ($/kg)**	**Mass**	**Price*Mass**	**Ratio**
Cobalt	52.76	0.04	2.32	0.053
Copper	9.05	0.71	6.43	0.15
Nickel	16.16	2.0	32.32	0.74
Ammonium sulphate	0.17	0.89	0.15	0.003
Nickel Sulphate	2.23	1.0	2.23	**0.051**
Sum	**80.37**		**43.44**	**1.0**

Appendix C: Inventory for LCA and Parameterization.

1. Parameterization model:



	Mining and Beneficiation			elting (ma	Nickel Sulphate		
	Ore Grades	Mine type	Beneficiation recovery efficiency (%)	Smelting recovery efficiency (%)	Electricity Mix	Nickel recovery	Allocation type
Nickel	2%	underground	98%	98%	NO	98%	mass

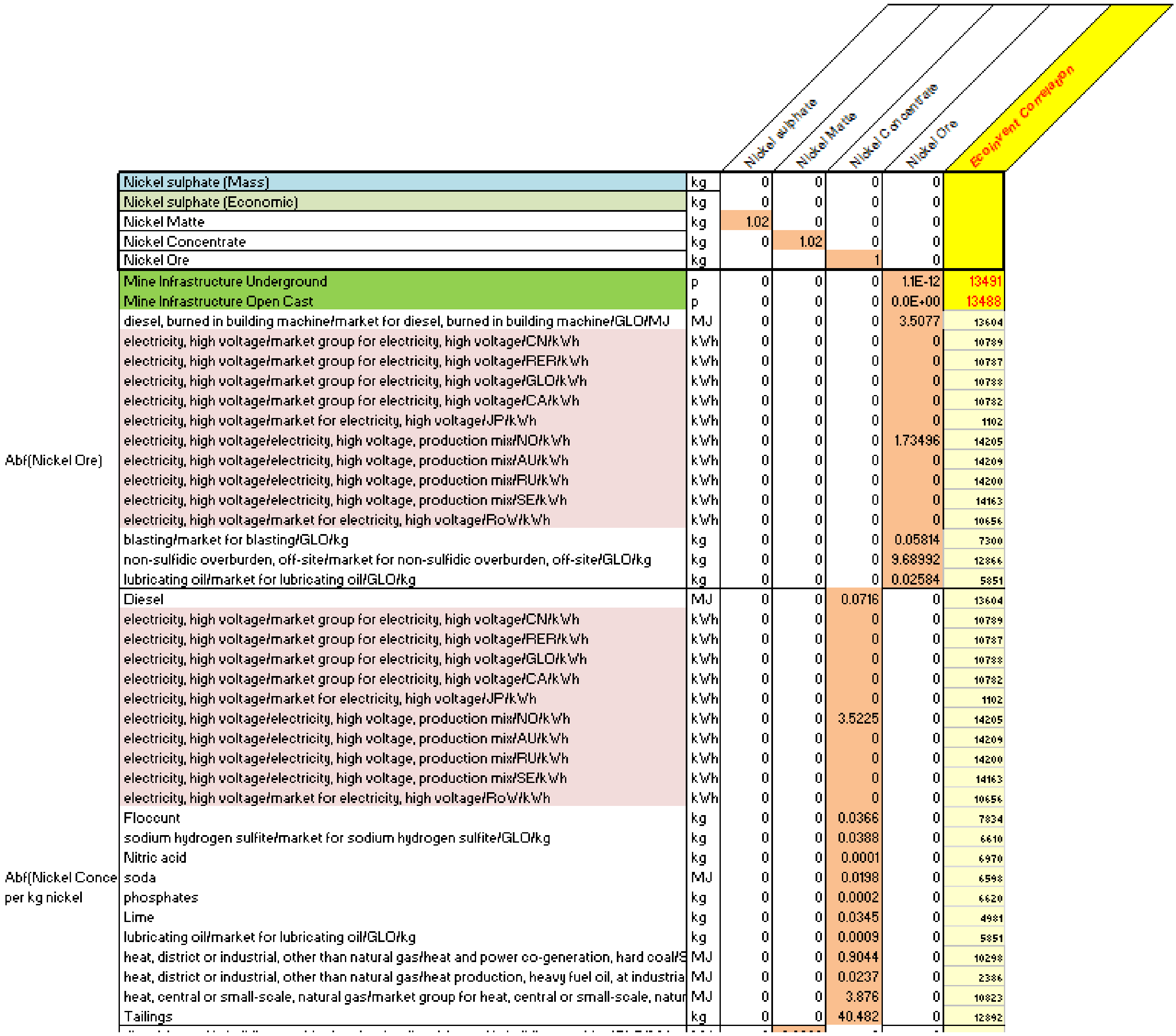
Figure 20. Parameters

The table in figure 20 id made in excel that where all the parameters are with their values are added. This table makes all the different scenario through different combinations of the values for parameters. In the table one scenario is mentioned where ore grade is 2%, mine-type is underground, recovery from beneficiation is 98%, from smelting and refining is also 98%, electricity mix used is Norway and the allocation type is mass allocation. By changing different values for the parameter, we have 720 scenarios created.

Figures 21, 22 and 23 show the inventory used for parameterization. First 6 rows in figure 21 show the foreground while all the other flows in figures 21, 22 and 23 are in the background system. In this inventory all the inputs and outputs that are affected by the parameters are given a formula linked to the parameters table (figure 20). The change in the parameters directly changes the values in the parameterization inventory according to the change in parameters. For example, an Excel formula for electricity input to nickel sulphate refining for global electricity mix will be:

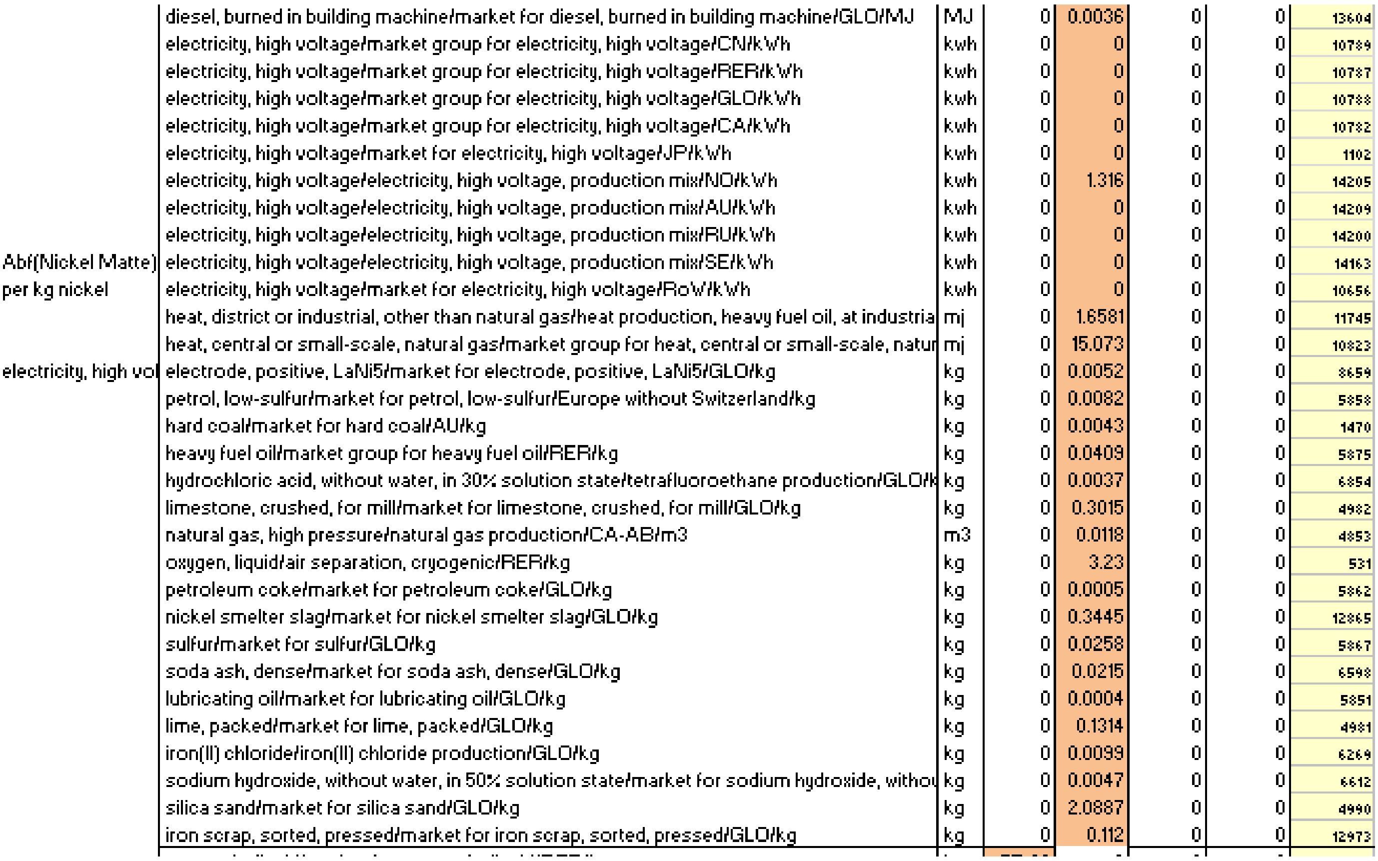
=IF((AND(V3="GLO", X3="mass")), 2.5, IF((AND(V3="GLO", X3="eco")),0.6,0))

The formula simply says that if the electricity mix is global and the allocation type is mass allocation then enter the value 2.5. and if the mix is global and economic allocation is done then enter the value 0.6.



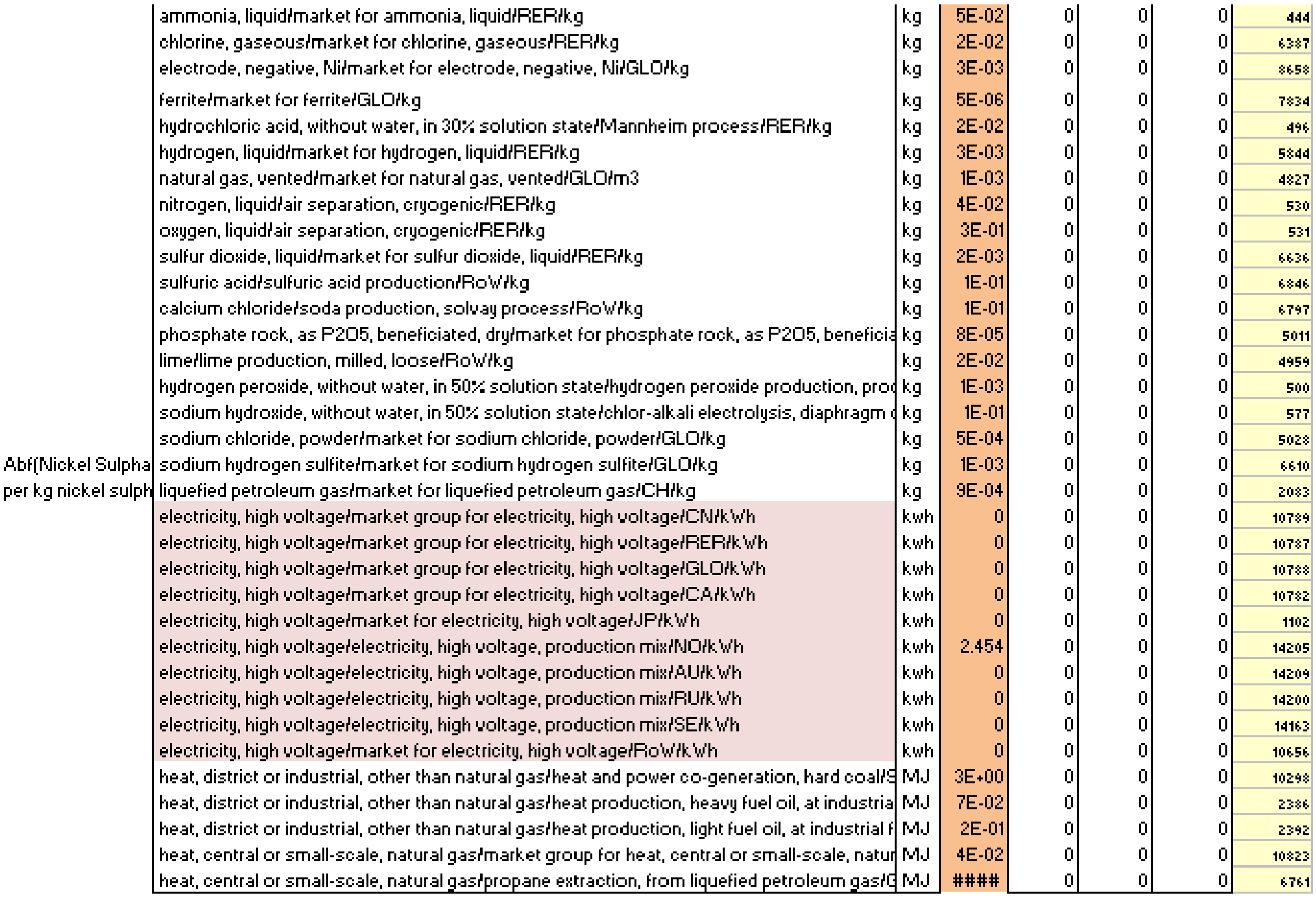
			Nickel sulphate	Nickel Matte	Nickel Concentrate	Nickel Ore	Ecoinvent Correlation
	Nickel sulphate (Mass)	kg	0	0	0	0	
	Nickel sulphate (Economic)	kg	0	0	0	0	
	Nickel Matte	kg	1.02	0	0	0	
	Nickel Concentrate	kg	0	1.02	0	0	
	Nickel Ore	kg			1	0	
	Mine Infrastructure Underground	p	0	0	0	1.1E-12	13491
	Mine Infrastructure Open Cast	p	0	0	0	0.0E+00	13488
	diesel, burned in building machine/market for diesel, burned in building machine/GLO/MJ	MJ	0	0	0	3.5077	13604
	electricity, high voltage/market group for electricity, high voltage/CN/kWh	kWh	0	0	0	0	10789
	electricity, high voltage/market group for electricity, high voltage/RER/kWh	kWh	0	0	0	0	10787
	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	kWh	0	0	0	0	10788
	electricity, high voltage/market group for electricity, high voltage/CA/kWh	kWh	0	0	0	0	10782
	electricity, high voltage/market for electricity, high voltage/JP/kWh	kWh	0	0	0	0	1102
	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	kWh	0	0	0	1.73496	14205
Abf(Nickel Ore)	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	kWh	0	0	0	0	14209
	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	kWh	0	0	0	0	14200
	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	kWh	0	0	0	0	14163
	electricity, high voltage/market for electricity, high voltage/RoW/kWh	kWh	0	0	0	0	10656
	blasting/market for blasting/GLO/kg	kg	0	0	0	0.05814	7300
	non-sulfidic overburden, off-site/market for non-sulfidic overburden, off-site/GLO/kg	kg	0	0	0	9.68992	12866
	lubricating oil/market for lubricating oil/GLO/kg	kg	0	0	0	0.02584	5851
	Diesel	MJ	0	0	0.0716	0	13604
	electricity, high voltage/market group for electricity, high voltage/CN/kWh	kWh	0	0	0	0	10789
	electricity, high voltage/market group for electricity, high voltage/RER/kWh	kWh	0	0	0	0	10787
	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	kWh	0	0	0	0	10788
	electricity, high voltage/market group for electricity, high voltage/CA/kWh	kWh	0	0	0	0	10782
	electricity, high voltage/market for electricity, high voltage/JP/kWh	kWh	0	0	0	0	1102
	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	kWh	0	0	3.5225	0	14205
	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	kWh	0	0	0	0	14209
	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	kWh	0	0	0	0	14200
	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	kWh	0	0	0	0	14163
	electricity, high voltage/market for electricity, high voltage/RoW/kWh	kWh	0	0	0	0	10656
	Floccunt	kg	0	0	0.0366	0	7834
	sodium hydrogen sulfite/market for sodium hydrogen sulfite/GLO/kg	kg	0	0	0.0388	0	6610
	Nitric acid	kg	0	0	0.0001	0	6970
Abf(Nickel Conce per kg nickel	soda	MJ	0	0	0.0198	0	6598
	phosphates	kg	0	0	0.0002	0	6620
	Lime	kg	0	0	0.0345	0	4981
	lubricating oil/market for lubricating oil/GLO/kg	kg	0	0	0.0009	0	5851
	heat, district or industrial, other than natural gas/heat and power co-generation, hard coal/S	MJ	0	0	0.9044	0	10298
	heat, district or industrial, other than natural gas/heat production, heavy fuel oil, at industria	MJ	0	0	0.0237	0	2386
	heat, central or small-scale, natural gas/market group for heat, central or small-scale, natur	MJ	0	0	3.876	0	10823
	Tailings	kg	0	0	40.482	0	12892

Figure 21. Parameterization inventory for mining and beneficiation.



	diesel, burned in building machine/market for diesel, burned in building machine/GLO/MJ	MJ	0	0.0036	0	0	13604
	electricity, high voltage/market group for electricity, high voltage/CN/kWh	kwh	0	0	0	0	10789
	electricity, high voltage/market group for electricity, high voltage/RER/kWh	kwh	0	0	0	0	10787
	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	kwh	0	0	0	0	10788
	electricity, high voltage/market group for electricity, high voltage/CA/kWh	kwh	0	0	0	0	10782
	electricity, high voltage/market for electricity, high voltage/JP/kWh	kwh	0	0	0	0	1102
	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	kwh	0	1.316	0	0	14205
	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	kwh	0	0	0	0	14209
	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	kwh	0	0	0	0	14200
Abf(Nickel Matte)	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	kwh	0	0	0	0	14163
per kg nickel	electricity, high voltage/market for electricity, high voltage/RoW/kWh	kwh	0	0	0	0	10656
	heat, district or industrial, other than natural gas/heat production, heavy fuel oil, at industria	mj	0	1.6581	0	0	11745
	heat, central or small-scale, natural gas/market group for heat, central or small-scale, natur	mj	0	15.073	0	0	10823
electricity, high vol	electrode, positive, LaNi5/market for electrode, positive, LaNi5/GLO/kg	kg	0	0.0052	0	0	8659
	petrol, low-sulfur/market for petrol, low-sulfur/Europe without Switzerland/kg	kg	0	0.0082	0	0	5858
	hard coal/market for hard coal/AU/kg	kg	0	0.0043	0	0	1470
	heavy fuel oil/market group for heavy fuel oil/RER/kg	kg	0	0.0409	0	0	5875
	hydrochloric acid, without water, in 30% solution state/tetrafluoroethane production/GLO/k	kg	0	0.0037	0	0	6854
	limestone, crushed, for mill/market for limestone, crushed, for mill/GLO/kg	kg	0	0.3015	0	0	4982
	natural gas, high pressure/natural gas production/CA-AB/m3	m3	0	0.0118	0	0	4853
	oxygen, liquid/air separation, cryogenic/RER/kg	kg	0	3.23	0	0	531
	petroleum coke/market for petroleum coke/GLO/kg	kg	0	0.0005	0	0	5862
	nickel smelter slag/market for nickel smelter slag/GLO/kg	kg	0	0.3445	0	0	12865
	sulfur/market for sulfur/GLO/kg	kg	0	0.0258	0	0	5867
	soda ash, dense/market for soda ash, dense/GLO/kg	kg	0	0.0215	0	0	6598
	lubricating oil/market for lubricating oil/GLO/kg	kg	0	0.0004	0	0	5851
	lime, packed/market for lime, packed/GLO/kg	kg	0	0.1314	0	0	4981
	iron(II) chloride/iron(II) chloride production/GLO/kg	kg	0	0.0099	0	0	6269
	sodium hydroxide, without water, in 50% solution state/market for sodium hydroxide, withou	kg	0	0.0047	0	0	6612
	silica sand/market for silica sand/GLO/kg	kg	0	2.0887	0	0	4990
	iron scrap, sorted, pressed/market for iron scrap, sorted, pressed/GLO/kg	kg	0	0.112	0	0	12973

Figure 22. Parameterization inventory for primary extraction.

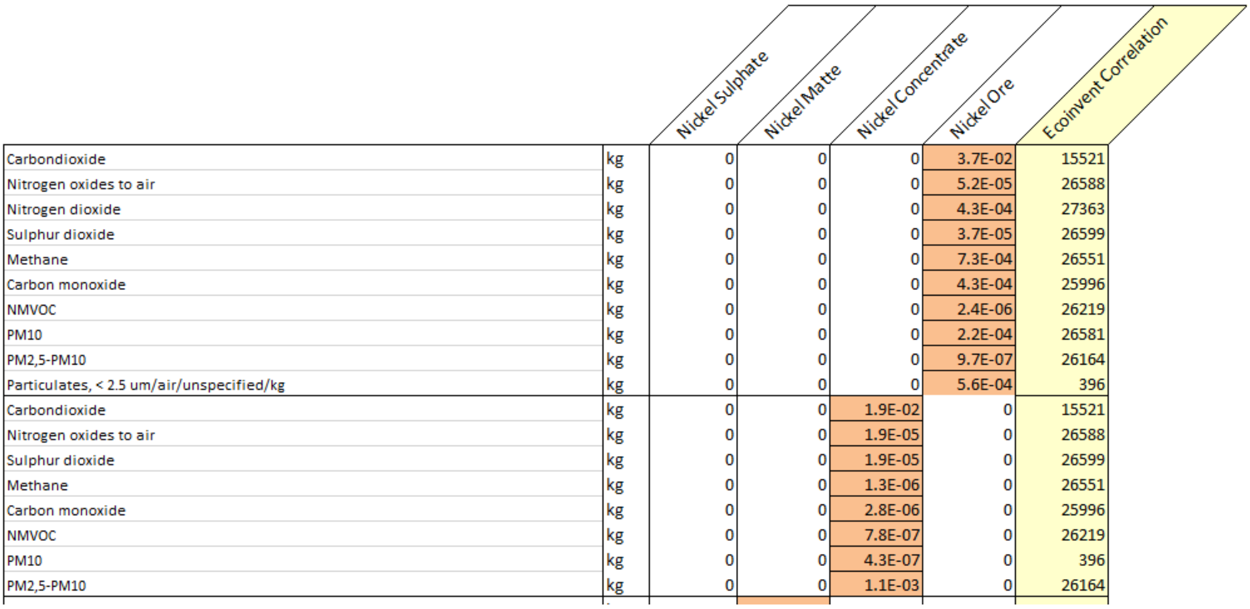


	ammonia, liquid/market for ammonia, liquid/RER/kg	kg	5E-02	0	0	0	444
	chlorine, gaseous/market for chlorine, gaseous/RER/kg	kg	2E-02	0	0	0	6387
	electrode, negative, Ni/market for electrode, negative, Ni/GLO/kg	kg	3E-03	0	0	0	8658
	ferrite/market for ferrite/GLO/kg	kg	5E-06	0	0	0	7834
	hydrochloric acid, without water, in 30% solution state/Mannheim process/RER/kg	kg	2E-02	0	0	0	496
	hydrogen, liquid/market for hydrogen, liquid/RER/kg	kg	3E-03	0	0	0	5844
	natural gas, vented/market for natural gas, vented/GLO/m3	kg	1E-03	0	0	0	4827
	nitrogen, liquid/air separation, cryogenic/RER/kg	kg	4E-02	0	0	0	530
	oxygen, liquid/air separation, cryogenic/RER/kg	kg	3E-01	0	0	0	531
	sulfur dioxide, liquid/market for sulfur dioxide, liquid/RER/kg	kg	2E-03	0	0	0	6636
	sulfuric acid/sulfuric acid production/RoW/kg	kg	1E-01	0	0	0	6846
	calcium chloride/soda production, solvay process/RoW/kg	kg	1E-01	0	0	0	6797
	phosphate rock, as P2O5, beneficiated, dry/market for phosphate rock, as P2O5, beneficia	kg	8E-05	0	0	0	5011
	lime/lime production, milled, loose/RoW/kg	kg	2E-02	0	0	0	4959
	hydrogen peroxide, without water, in 50% solution state/hydrogen peroxide production, pro	kg	1E-03	0	0	0	500
	sodium hydroxide, without water, in 50% solution state/chlor-alkali electrolysis, diaphragm	kg	1E-01	0	0	0	577
	sodium chloride, powder/market for sodium chloride, powder/GLO/kg	kg	5E-04	0	0	0	5028
Abf(Nickel Sulpha	sodium hydrogen sulfite/market for sodium hydrogen sulfite/GLO/kg	kg	1E-03	0	0	0	6610
per kg nickel sulph	liquefied petroleum gas/market for liquefied petroleum gas/CH/kg	kg	9E-04	0	0	0	2083
	electricity, high voltage/market group for electricity, high voltage/CN/kWh	kwh	0	0	0	0	10789
	electricity, high voltage/market group for electricity, high voltage/RER/kWh	kwh	0	0	0	0	10787
	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	kwh	0	0	0	0	10788
	electricity, high voltage/market group for electricity, high voltage/CA/kWh	kwh	0	0	0	0	10782
	electricity, high voltage/market for electricity, high voltage/JP/kWh	kwh	0	0	0	0	1102
	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	kwh	2.454	0	0	0	14205
	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	kwh	0	0	0	0	14209
	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	kwh	0	0	0	0	14200
	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	kwh	0	0	0	0	14163
	electricity, high voltage/market for electricity, high voltage/RoW/kWh	kwh	0	0	0	0	10656
	heat, district or industrial, other than natural gas/heat and power co-generation, hard coal/S	MJ	3E+00	0	0	0	10298
	heat, district or industrial, other than natural gas/heat production, heavy fuel oil, at industria	MJ	7E-02	0	0	0	2386
	heat, district or industrial, other than natural gas/heat production, light fuel oil, at industrial f	MJ	2E-01	0	0	0	2392
	heat, central or small-scale, natural gas/market group for heat, central or small-scale, natur	MJ	4E-02	0	0	0	10823
	heat, central or small-scale, natural gas/propane extraction, from liquefied petroleum gas/G	MJ	####	0	0	0	6761

Figure 23. Parameterization inventory for refining of nickel sulphate.

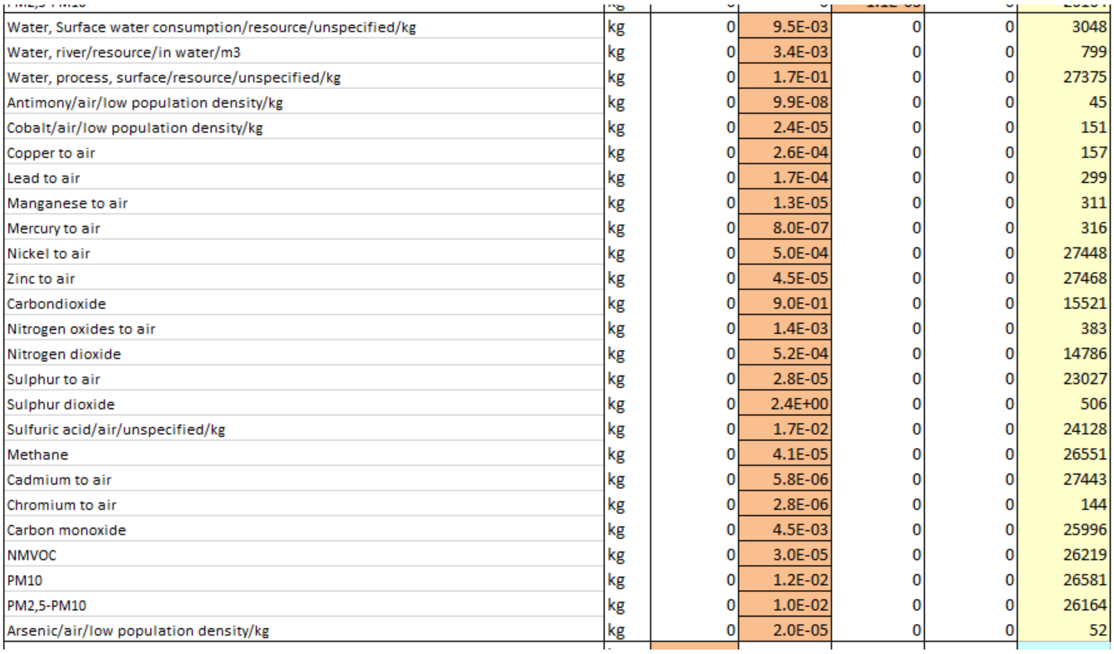
Similarly, figures 24, 25 and 26 present the emission matrix for the parameterization inventory and uses formulas for the values that are affected by the parameters.

Emissions are scaled with values from the based inventory and the respective input parameters



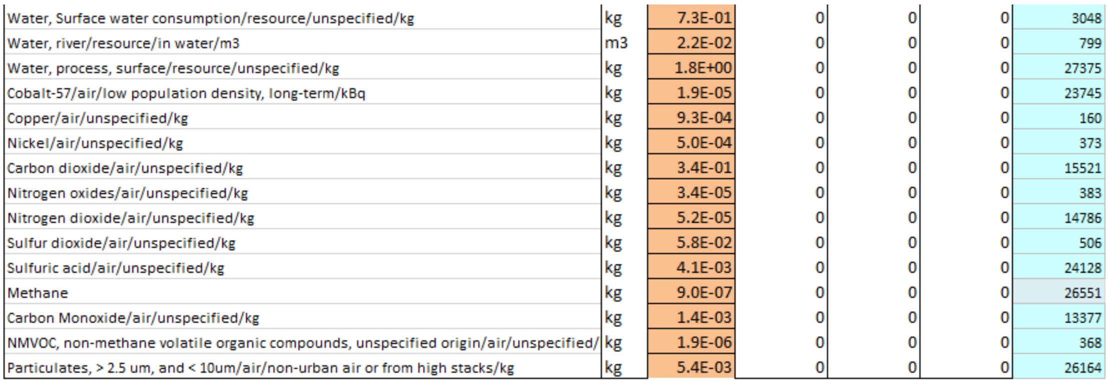
		Nickel Sulphate	Nickel Matte	Nickel Concentrate	Nickel Ore	Ecoinvent Correlation
Carbondioxide	kg	0	0	0	3.7E-02	15521
Nitrogen oxides to air	kg	0	0	0	5.2E-05	26588
Nitrogen dioxide	kg	0	0	0	4.3E-04	27363
Sulphur dioxide	kg	0	0	0	3.7E-05	26599
Methane	kg	0	0	0	7.3E-04	26551
Carbon monoxide	kg	0	0	0	4.3E-04	25996
NMVOC	kg	0	0	0	2.4E-06	26219
PM10	kg	0	0	0	2.2E-04	26581
PM2,5-PM10	kg	0	0	0	9.7E-07	26164
Particulates, < 2.5 um/air/unspecified/kg	kg	0	0	0	5.6E-04	396
Carbondioxide	kg	0	0	1.9E-02	0	15521
Nitrogen oxides to air	kg	0	0	1.9E-05	0	26588
Sulphur dioxide	kg	0	0	1.9E-05	0	26599
Methane	kg	0	0	1.3E-06	0	26551
Carbon monoxide	kg	0	0	2.8E-06	0	25996
NMVOC	kg	0	0	7.8E-07	0	26219
PM10	kg	0	0	4.3E-07	0	396
PM2,5-PM10	kg	0	0	1.1E-03	0	26164

Figure 24. Emission matrix for parameterization inventory for mining and beneficiation.



Water, Surface water consumption/resource/unspecified/kg	kg	0	9.5E-03	0	0	3048
Water, river/resource/in water/m3	kg	0	3.4E-03	0	0	799
Water, process, surface/resource/unspecified/kg	kg	0	1.7E-01	0	0	27375
Antimony/air/low population density/kg	kg	0	9.9E-08	0	0	45
Cobalt/air/low population density/kg	kg	0	2.4E-05	0	0	151
Copper to air	kg	0	2.6E-04	0	0	157
Lead to air	kg	0	1.7E-04	0	0	299
Manganese to air	kg	0	1.3E-05	0	0	311
Mercury to air	kg	0	8.0E-07	0	0	316
Nickel to air	kg	0	5.0E-04	0	0	27448
Zinc to air	kg	0	4.5E-05	0	0	27468
Carbondioxide	kg	0	9.0E-01	0	0	15521
Nitrogen oxides to air	kg	0	1.4E-03	0	0	383
Nitrogen dioxide	kg	0	5.2E-04	0	0	14786
Sulphur to air	kg	0	2.8E-05	0	0	23027
Sulphur dioxide	kg	0	2.4E+00	0	0	506
Sulfuric acid/air/unspecified/kg	kg	0	1.7E-02	0	0	24128
Methane	kg	0	4.1E-05	0	0	26551
Cadmium to air	kg	0	5.8E-06	0	0	27443
Chromium to air	kg	0	2.8E-06	0	0	144
Carbon monoxide	kg	0	4.5E-03	0	0	25996
NMVOC	kg	0	3.0E-05	0	0	26219
PM10	kg	0	1.2E-02	0	0	26581
PM2,5-PM10	kg	0	1.0E-02	0	0	26164
Arsenic/air/low population density/kg	kg	0	2.0E-05	0	0	52

Figure 25. Emission matrix for parameterization inventory for primary extraction.

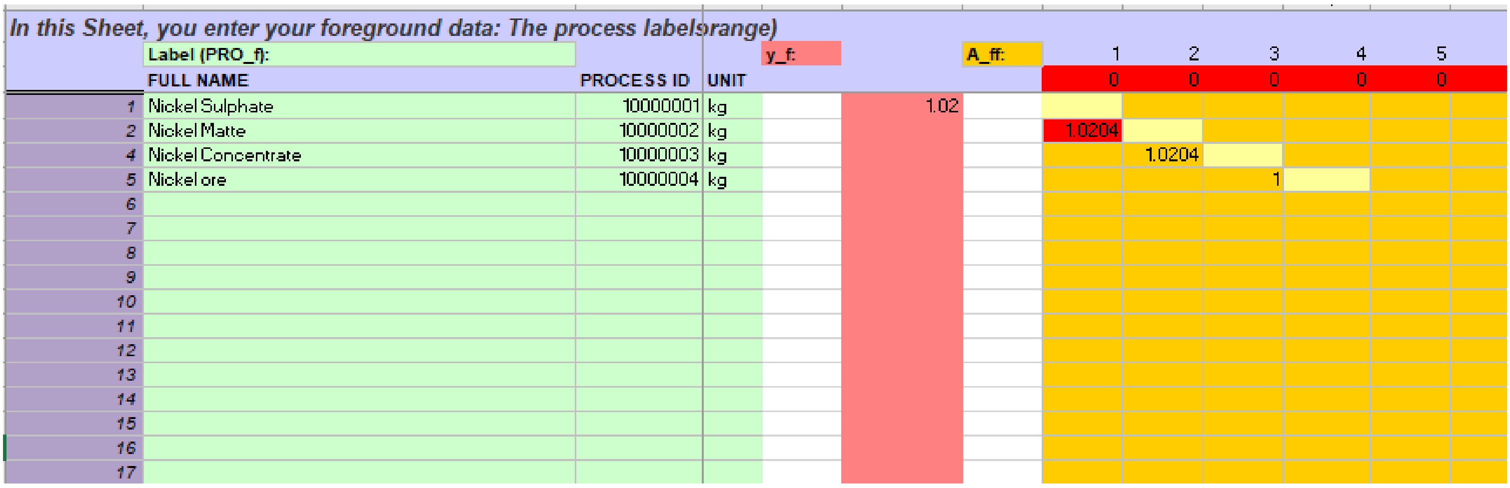


Water, Surface water consumption/resource/unspecified/kg	kg	7.3E-01	0	0	0	3048
Water, river/resource/in water/m3	m3	2.2E-02	0	0	0	799
Water, process, surface/resource/unspecified/kg	kg	1.8E+00	0	0	0	27375
Cobalt-57/air/low population density, long-term/kBq	kg	1.9E-05	0	0	0	23745
Copper/air/unspecified/kg	kg	9.3E-04	0	0	0	160
Nickel/air/unspecified/kg	kg	5.0E-04	0	0	0	373
Carbon dioxide/air/unspecified/kg	kg	3.4E-01	0	0	0	15521
Nitrogen oxides/air/unspecified/kg	kg	3.4E-05	0	0	0	383
Nitrogen dioxide/air/unspecified/kg	kg	5.2E-05	0	0	0	14786
Sulfur dioxide/air/unspecified/kg	kg	5.8E-02	0	0	0	506
Sulfuric acid/air/unspecified/kg	kg	4.1E-03	0	0	0	24128
Methane	kg	9.0E-07	0	0	0	26551
Carbon Monoxide/air/unspecified/kg	kg	1.4E-03	0	0	0	13377
NMVOC, non-methane volatile organic compounds, unspecified origin/air/unspecified/	kg	1.9E-06	0	0	0	368
Particulates, > 2.5 um, and < 10um/air/non-urban air or from high stacks/kg	kg	5.4E-03	0	0	0	26164

Figure 26. Emission matrix for parameterization inventory for refining.

2. Arda LCA

For LCA, the foreground matrix is presented in figure 27.

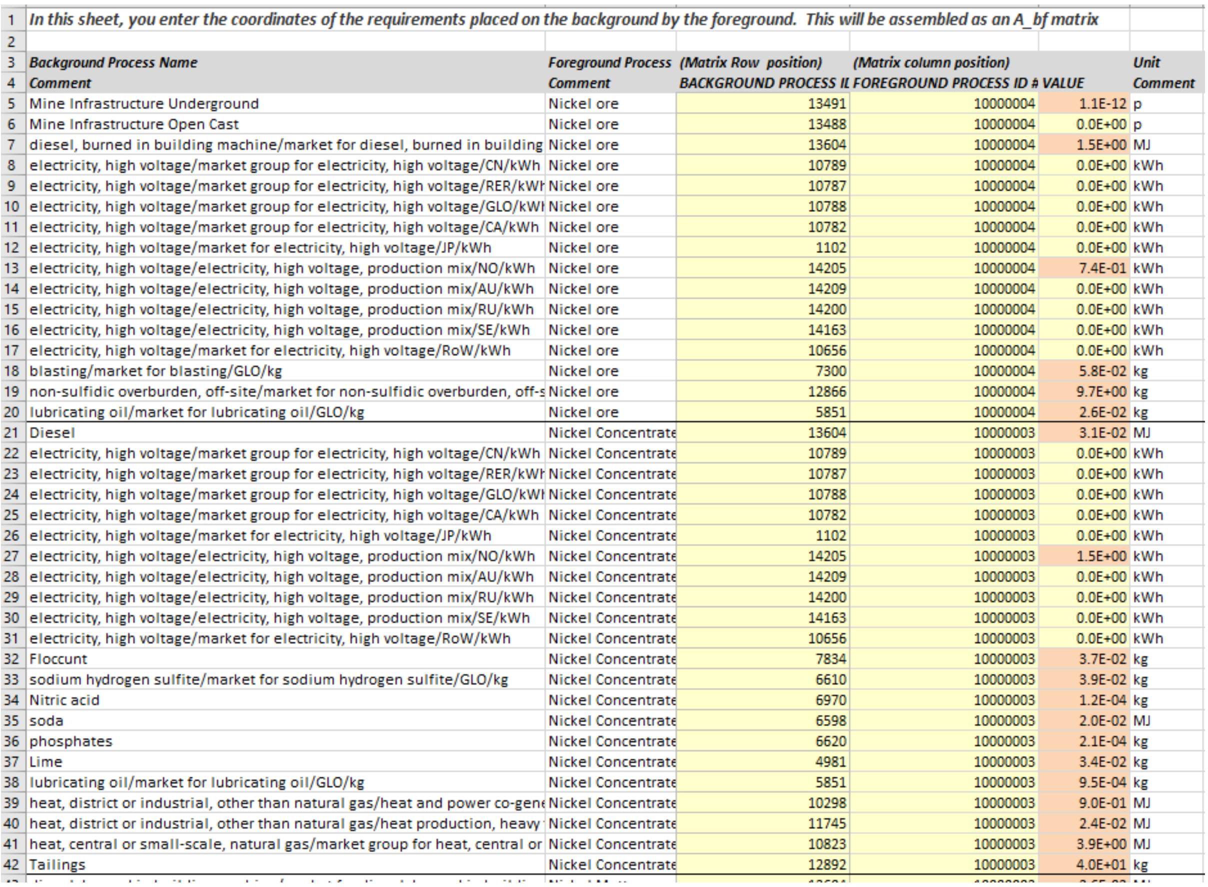


In this Sheet, you enter your foreground data: The process labelsorange)

	Label (PRO_f):			y_f:		A_ff:	1	2	3	4	5
	FULL NAME	PROCESS ID	UNIT				0	0	0	0	0
1	Nickel Sulphate	10000001	kg		1.02						
2	Nickel Matte	10000002	kg				1.0204				
4	Nickel Concentrate	10000003	kg					1.0204			
5	Nickel ore	10000004	kg						1		
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											

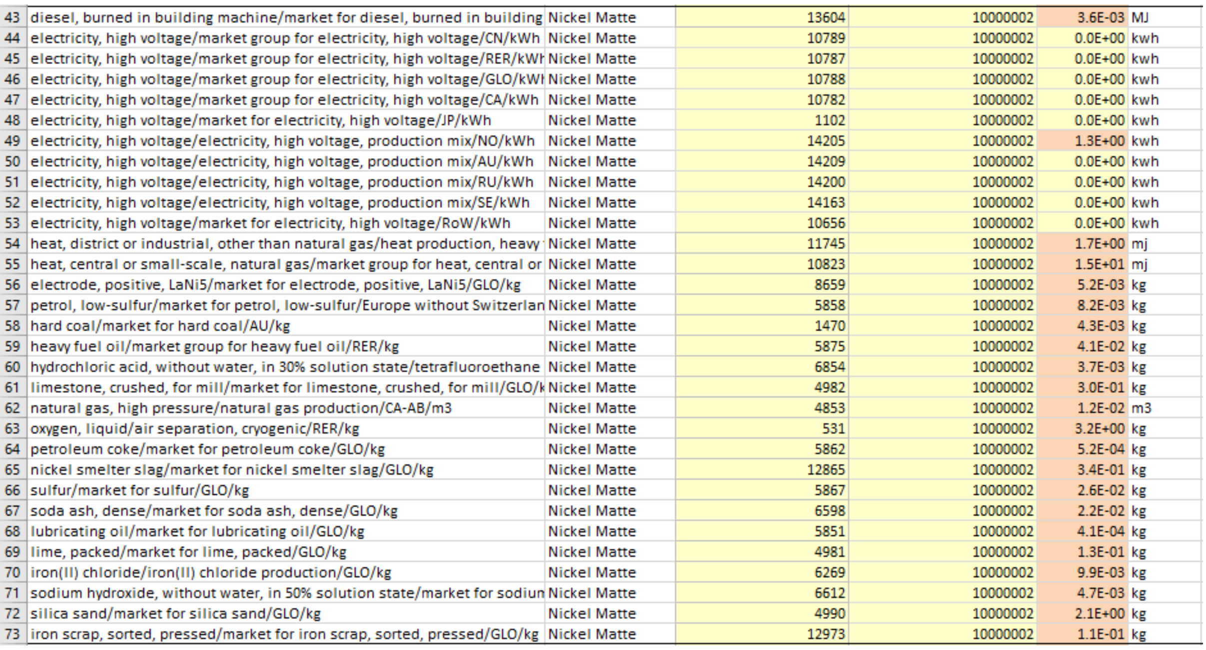
Figure 27. Foreground matrix

Figure 28, 29 and 30 present the background inventory for production of nickel sulphate. Al the inputs are lined to the parameterization inventory. When there is a change in the parameterization inventory, the values in LCA inventory also change. Figure 31, 32 and 33 are the stressors from the nickel sulphate production used in the assessment and are lined to the stressors in the parameterization inventory.



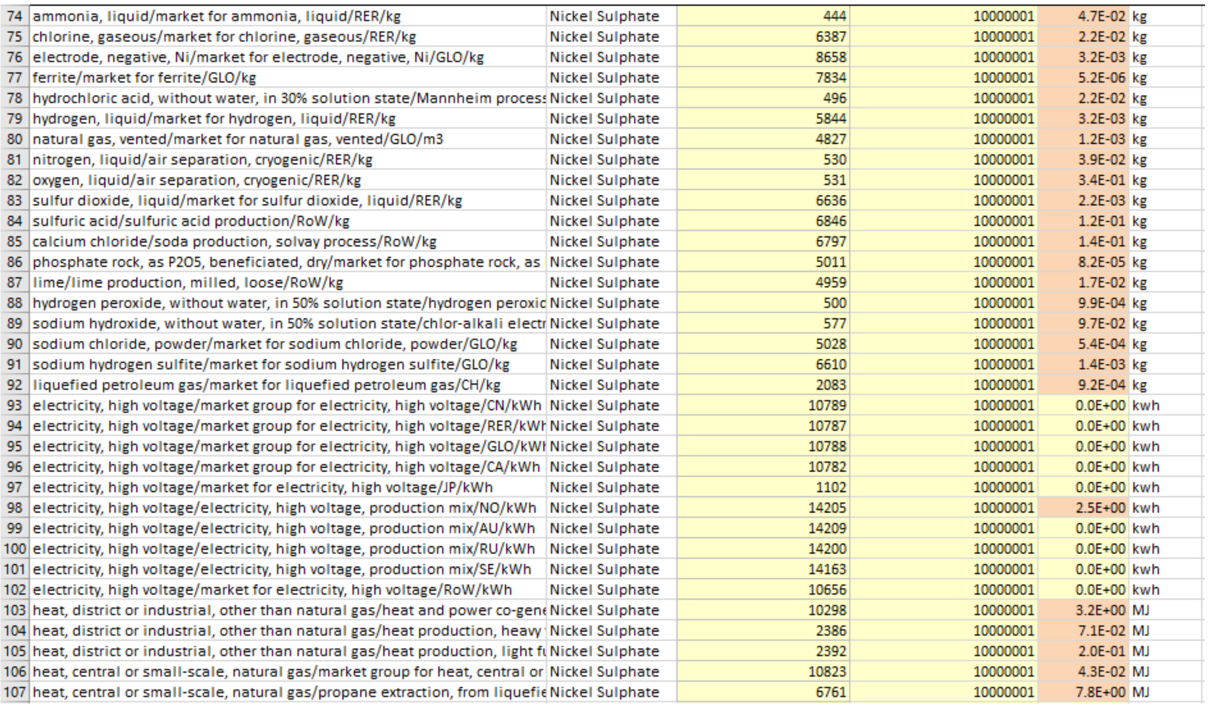
1	*In this sheet, you enter the coordinates of the requirements placed on the background by the foreground. This will be assembled as an A_bf matrix*					
2						
3	***Background Process Name***	***Foreground Process***	***(Matrix Row position)***	***(Matrix column position)***		***Unit***
4	***Comment***	***Comment***	***BACKGROUND PROCESS IL***	***FOREGROUND PROCESS ID #***	***VALUE***	***Comment***
5	Mine Infrastructure Underground	Nickel ore	13491	10000004	1.1E-12	p
6	Mine Infrastructure Open Cast	Nickel ore	13488	10000004	0.0E+00	p
7	diesel, burned in building machine/market for diesel, burned in building	Nickel ore	13604	10000004	1.5E+00	MJ
8	electricity, high voltage/market group for electricity, high voltage/CN/kWh	Nickel ore	10789	10000004	0.0E+00	kWh
9	electricity, high voltage/market group for electricity, high voltage/RER/kWh	Nickel ore	10787	10000004	0.0E+00	kWh
10	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	Nickel ore	10788	10000004	0.0E+00	kWh
11	electricity, high voltage/market group for electricity, high voltage/CA/kWh	Nickel ore	10782	10000004	0.0E+00	kWh
12	electricity, high voltage/market for electricity, high voltage/JP/kWh	Nickel ore	1102	10000004	0.0E+00	kWh
13	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	Nickel ore	14205	10000004	7.4E-01	kWh
14	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	Nickel ore	14209	10000004	0.0E+00	kWh
15	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	Nickel ore	14200	10000004	0.0E+00	kWh
16	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	Nickel ore	14163	10000004	0.0E+00	kWh
17	electricity, high voltage/market for electricity, high voltage/RoW/kWh	Nickel ore	10656	10000004	0.0E+00	kWh
18	blasting/market for blasting/GLO/kg	Nickel ore	7300	10000004	5.8E-02	kg
19	non-sulfidic overburden, off-site/market for non-sulfidic overburden, off-s	Nickel ore	12866	10000004	9.7E+00	kg
20	lubricating oil/market for lubricating oil/GLO/kg	Nickel ore	5851	10000004	2.6E-02	kg
21	Diesel	Nickel Concentrate	13604	10000003	3.1E-02	MJ
22	electricity, high voltage/market group for electricity, high voltage/CN/kWh	Nickel Concentrate	10789	10000003	0.0E+00	kWh
23	electricity, high voltage/market group for electricity, high voltage/RER/kWh	Nickel Concentrate	10787	10000003	0.0E+00	kWh
24	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	Nickel Concentrate	10788	10000003	0.0E+00	kWh
25	electricity, high voltage/market group for electricity, high voltage/CA/kWh	Nickel Concentrate	10782	10000003	0.0E+00	kWh
26	electricity, high voltage/market for electricity, high voltage/JP/kWh	Nickel Concentrate	1102	10000003	0.0E+00	kWh
27	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	Nickel Concentrate	14205	10000003	1.5E+00	kWh
28	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	Nickel Concentrate	14209	10000003	0.0E+00	kWh
29	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	Nickel Concentrate	14200	10000003	0.0E+00	kWh
30	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	Nickel Concentrate	14163	10000003	0.0E+00	kWh
31	electricity, high voltage/market for electricity, high voltage/RoW/kWh	Nickel Concentrate	10656	10000003	0.0E+00	kWh
32	Floccunt	Nickel Concentrate	7834	10000003	3.7E-02	kg
33	sodium hydrogen sulfite/market for sodium hydrogen sulfite/GLO/kg	Nickel Concentrate	6610	10000003	3.9E-02	kg
34	Nitric acid	Nickel Concentrate	6970	10000003	1.2E-04	kg
35	soda	Nickel Concentrate	6598	10000003	2.0E-02	MJ
36	phosphates	Nickel Concentrate	6620	10000003	2.1E-04	kg
37	Lime	Nickel Concentrate	4981	10000003	3.4E-02	kg
38	lubricating oil/market for lubricating oil/GLO/kg	Nickel Concentrate	5851	10000003	9.5E-04	kg
39	heat, district or industrial, other than natural gas/heat and power co-gene	Nickel Concentrate	10298	10000003	9.0E-01	MJ
40	heat, district or industrial, other than natural gas/heat production, heavy	Nickel Concentrate	11745	10000003	2.4E-02	MJ
41	heat, central or small-scale, natural gas/market group for heat, central or	Nickel Concentrate	10823	10000003	3.9E+00	MJ
42	Tailings	Nickel Concentrate	12892	10000003	4.0E+01	kg

Figure 28. Background inventory for LCA for mining and beneficiation.



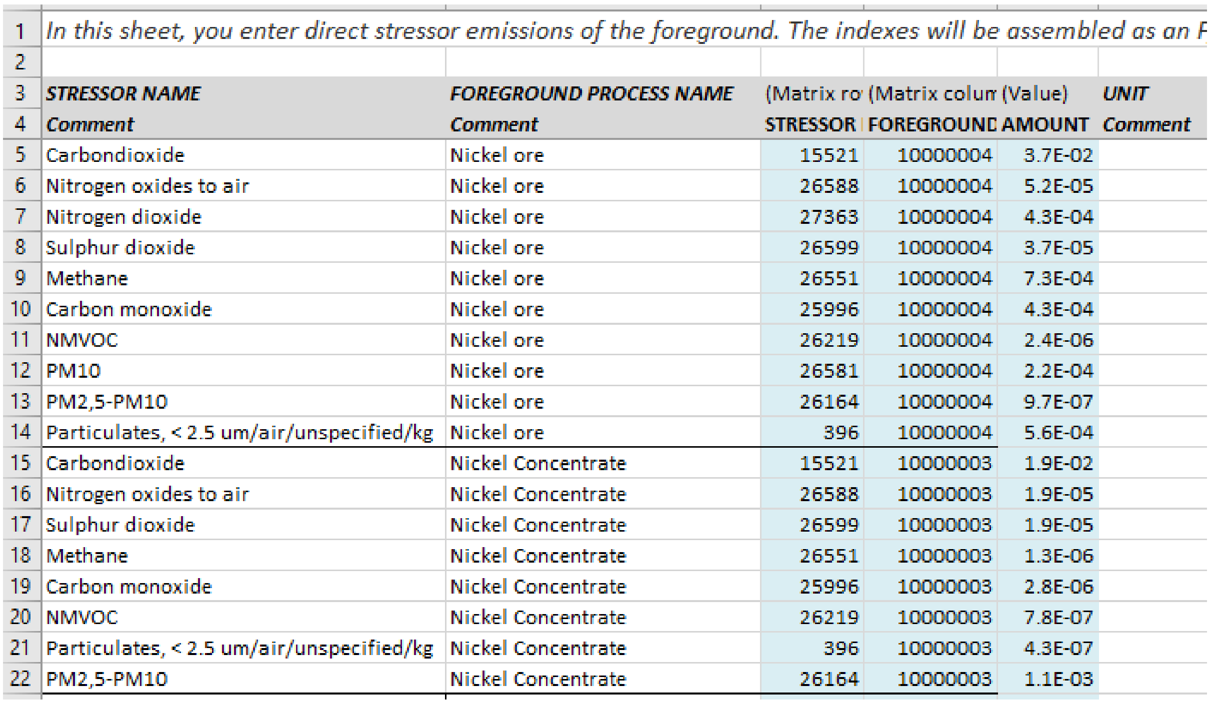
43	diesel, burned in building machine/market for diesel, burned in building	Nickel Matte	13604	10000002	3.6E-03	MJ
44	electricity, high voltage/market group for electricity, high voltage/CN/kWh	Nickel Matte	10789	10000002	0.0E+00	kwh
45	electricity, high voltage/market group for electricity, high voltage/RER/kWh	Nickel Matte	10787	10000002	0.0E+00	kwh
46	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	Nickel Matte	10788	10000002	0.0E+00	kwh
47	electricity, high voltage/market group for electricity, high voltage/CA/kWh	Nickel Matte	10782	10000002	0.0E+00	kwh
48	electricity, high voltage/market for electricity, high voltage/JP/kWh	Nickel Matte	1102	10000002	0.0E+00	kwh
49	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	Nickel Matte	14205	10000002	1.3E+00	kwh
50	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	Nickel Matte	14209	10000002	0.0E+00	kwh
51	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	Nickel Matte	14200	10000002	0.0E+00	kwh
52	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	Nickel Matte	14163	10000002	0.0E+00	kwh
53	electricity, high voltage/market for electricity, high voltage/RoW/kWh	Nickel Matte	10656	10000002	0.0E+00	kwh
54	heat, district or industrial, other than natural gas/heat production, heavy	Nickel Matte	11745	10000002	1.7E+00	mj
55	heat, central or small-scale, natural gas/market group for heat, central or	Nickel Matte	10823	10000002	1.5E+01	mj
56	electrode, positive, LaNi5/market for electrode, positive, LaNi5/GLO/kg	Nickel Matte	8659	10000002	5.2E-03	kg
57	petrol, low-sulfur/market for petrol, low-sulfur/Europe without Switzerlan	Nickel Matte	5858	10000002	8.2E-03	kg
58	hard coal/market for hard coal/AU/kg	Nickel Matte	1470	10000002	4.3E-03	kg
59	heavy fuel oil/market group for heavy fuel oil/RER/kg	Nickel Matte	5875	10000002	4.1E-02	kg
60	hydrochloric acid, without water, in 30% solution state/tetrafluoroethane	Nickel Matte	6854	10000002	3.7E-03	kg
61	limestone, crushed, for mill/market for limestone, crushed, for mill/GLO/k	Nickel Matte	4982	10000002	3.0E-01	kg
62	natural gas, high pressure/natural gas production/CA-AB/m3	Nickel Matte	4853	10000002	1.2E-02	m3
63	oxygen, liquid/air separation, cryogenic/RER/kg	Nickel Matte	531	10000002	3.2E+00	kg
64	petroleum coke/market for petroleum coke/GLO/kg	Nickel Matte	5862	10000002	5.2E-04	kg
65	nickel smelter slag/market for nickel smelter slag/GLO/kg	Nickel Matte	12865	10000002	3.4E-01	kg
66	sulfur/market for sulfur/GLO/kg	Nickel Matte	5867	10000002	2.6E-02	kg
67	soda ash, dense/market for soda ash, dense/GLO/kg	Nickel Matte	6598	10000002	2.2E-02	kg
68	lubricating oil/market for lubricating oil/GLO/kg	Nickel Matte	5851	10000002	4.1E-04	kg
69	lime, packed/market for lime, packed/GLO/kg	Nickel Matte	4981	10000002	1.3E-01	kg
70	iron(II) chloride/iron(II) chloride production/GLO/kg	Nickel Matte	6269	10000002	9.9E-03	kg
71	sodium hydroxide, without water, in 50% solution state/market for sodiun	Nickel Matte	6612	10000002	4.7E-03	kg
72	silica sand/market for silica sand/GLO/kg	Nickel Matte	4990	10000002	2.1E+00	kg
73	iron scrap, sorted, pressed/market for iron scrap, sorted, pressed/GLO/kg	Nickel Matte	12973	10000002	1.1E-01	kg

Figure 29. Background inventory for LCA for primary extraction.



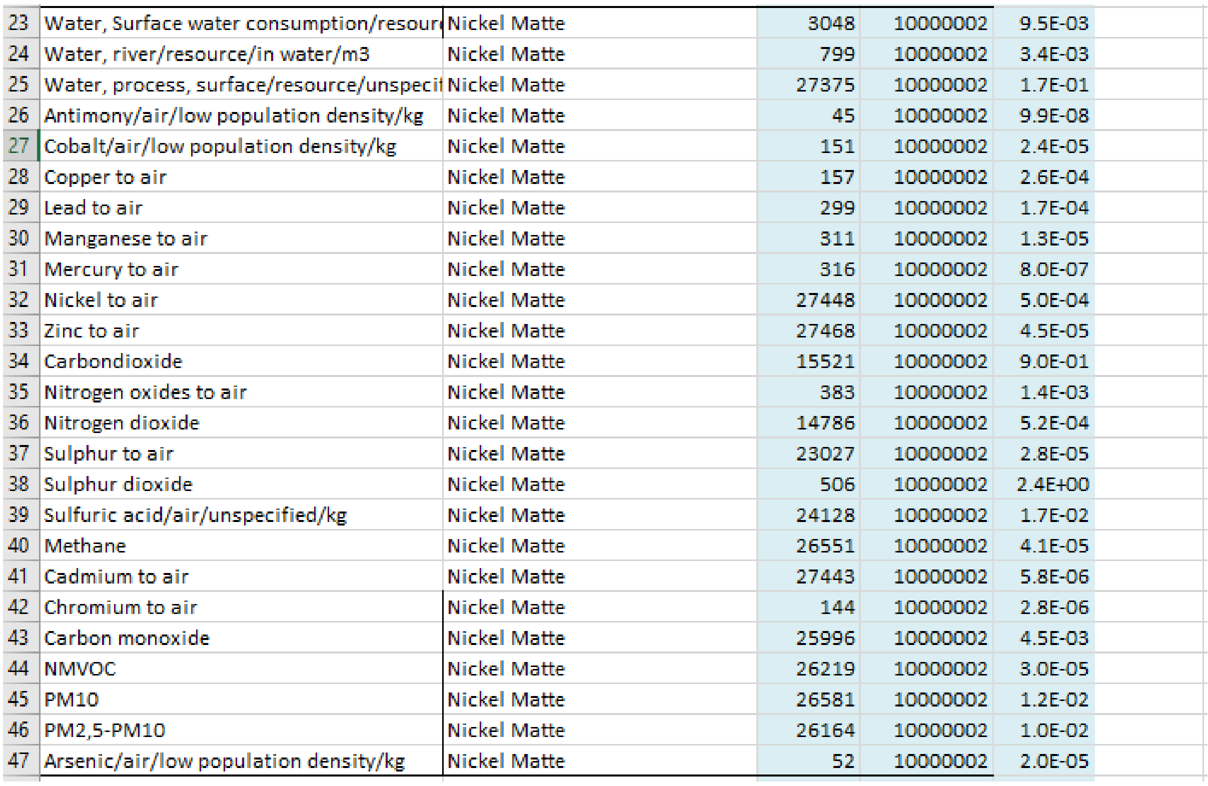
74	ammonia, liquid/market for ammonia, liquid/RER/kg	Nickel Sulphate	444	10000001	4.7E-02	kg
75	chlorine, gaseous/market for chlorine, gaseous/RER/kg	Nickel Sulphate	6387	10000001	2.2E-02	kg
76	electrode, negative, Ni/market for electrode, negative, Ni/GLO/kg	Nickel Sulphate	8658	10000001	3.2E-03	kg
77	ferrite/market for ferrite/GLO/kg	Nickel Sulphate	7834	10000001	5.2E-06	kg
78	hydrochloric acid, without water, in 30% solution state/Mannheim process	Nickel Sulphate	496	10000001	2.2E-02	kg
79	hydrogen, liquid/market for hydrogen, liquid/RER/kg	Nickel Sulphate	5844	10000001	3.2E-03	kg
80	natural gas, vented/market for natural gas, vented/GLO/m3	Nickel Sulphate	4827	10000001	1.2E-03	kg
81	nitrogen, liquid/air separation, cryogenic/RER/kg	Nickel Sulphate	530	10000001	3.9E-02	kg
82	oxygen, liquid/air separation, cryogenic/RER/kg	Nickel Sulphate	531	10000001	3.4E-01	kg
83	sulfur dioxide, liquid/market for sulfur dioxide, liquid/RER/kg	Nickel Sulphate	6636	10000001	2.2E-03	kg
84	sulfuric acid/sulfuric acid production/RoW/kg	Nickel Sulphate	6846	10000001	1.2E-01	kg
85	calcium chloride/soda production, solvay process/RoW/kg	Nickel Sulphate	6797	10000001	1.4E-01	kg
86	phosphate rock, as P2O5, beneficiated, dry/market for phosphate rock, as	Nickel Sulphate	5011	10000001	8.2E-05	kg
87	lime/lime production, milled, loose/RoW/kg	Nickel Sulphate	4959	10000001	1.7E-02	kg
88	hydrogen peroxide, without water, in 50% solution state/hydrogen peroxic	Nickel Sulphate	500	10000001	9.9E-04	kg
89	sodium hydroxide, without water, in 50% solution state/chlor-alkali electr	Nickel Sulphate	577	10000001	9.7E-02	kg
90	sodium chloride, powder/market for sodium chloride, powder/GLO/kg	Nickel Sulphate	5028	10000001	5.4E-04	kg
91	sodium hydrogen sulfite/market for sodium hydrogen sulfite/GLO/kg	Nickel Sulphate	6610	10000001	1.4E-03	kg
92	liquefied petroleum gas/market for liquefied petroleum gas/CH/kg	Nickel Sulphate	2083	10000001	9.2E-04	kg
93	electricity, high voltage/market group for electricity, high voltage/CN/kWh	Nickel Sulphate	10789	10000001	0.0E+00	kwh
94	electricity, high voltage/market group for electricity, high voltage/RER/kWh	Nickel Sulphate	10787	10000001	0.0E+00	kwh
95	electricity, high voltage/market group for electricity, high voltage/GLO/kWh	Nickel Sulphate	10788	10000001	0.0E+00	kwh
96	electricity, high voltage/market group for electricity, high voltage/CA/kWh	Nickel Sulphate	10782	10000001	0.0E+00	kwh
97	electricity, high voltage/market for electricity, high voltage/JP/kWh	Nickel Sulphate	1102	10000001	0.0E+00	kwh
98	electricity, high voltage/electricity, high voltage, production mix/NO/kWh	Nickel Sulphate	14205	10000001	2.5E+00	kwh
99	electricity, high voltage/electricity, high voltage, production mix/AU/kWh	Nickel Sulphate	14209	10000001	0.0E+00	kwh
100	electricity, high voltage/electricity, high voltage, production mix/RU/kWh	Nickel Sulphate	14200	10000001	0.0E+00	kwh
101	electricity, high voltage/electricity, high voltage, production mix/SE/kWh	Nickel Sulphate	14163	10000001	0.0E+00	kwh
102	electricity, high voltage/market for electricity, high voltage/RoW/kWh	Nickel Sulphate	10656	10000001	0.0E+00	kwh
103	heat, district or industrial, other than natural gas/heat and power co-gene	Nickel Sulphate	10298	10000001	3.2E+00	MJ
104	heat, district or industrial, other than natural gas/heat production, heavy	Nickel Sulphate	2386	10000001	7.1E-02	MJ
105	heat, district or industrial, other than natural gas/heat production, light fu	Nickel Sulphate	2392	10000001	2.0E-01	MJ
106	heat, central or small-scale, natural gas/market group for heat, central or	Nickel Sulphate	10823	10000001	4.3E-02	MJ
107	heat, central or small-scale, natural gas/propane extraction, from liquefie	Nickel Sulphate	6761	10000001	7.8E+00	MJ

Figure 30. Background inventory for LCA for refining.



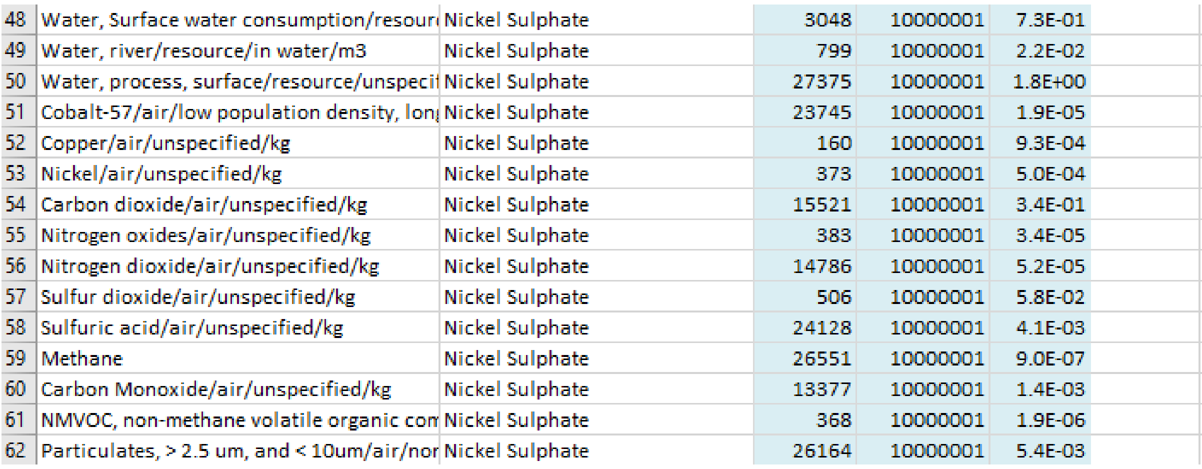
1	*In this sheet, you enter direct stressor emissions of the foreground. The indexes will be assembled as an F*					
2						
3	***STRESSOR NAME***	***FOREGROUND PROCESS NAME***	(Matrix ro	(Matrix colum	(Value)	***UNIT***
4	***Comment***	***Comment***	**STRESSOR**	**FOREGROUND**	**AMOUNT**	***Comment***
5	Carbondioxide	Nickel ore	15521	10000004	3.7E-02	
6	Nitrogen oxides to air	Nickel ore	26588	10000004	5.2E-05	
7	Nitrogen dioxide	Nickel ore	27363	10000004	4.3E-04	
8	Sulphur dioxide	Nickel ore	26599	10000004	3.7E-05	
9	Methane	Nickel ore	26551	10000004	7.3E-04	
10	Carbon monoxide	Nickel ore	25996	10000004	4.3E-04	
11	NMVOC	Nickel ore	26219	10000004	2.4E-06	
12	PM10	Nickel ore	26581	10000004	2.2E-04	
13	PM2,5-PM10	Nickel ore	26164	10000004	9.7E-07	
14	Particulates, < 2.5 um/air/unspecified/kg	Nickel ore	396	10000004	5.6E-04	
15	Carbondioxide	Nickel Concentrate	15521	10000003	1.9E-02	
16	Nitrogen oxides to air	Nickel Concentrate	26588	10000003	1.9E-05	
17	Sulphur dioxide	Nickel Concentrate	26599	10000003	1.9E-05	
18	Methane	Nickel Concentrate	26551	10000003	1.3E-06	
19	Carbon monoxide	Nickel Concentrate	25996	10000003	2.8E-06	
20	NMVOC	Nickel Concentrate	26219	10000003	7.8E-07	
21	Particulates, < 2.5 um/air/unspecified/kg	Nickel Concentrate	396	10000003	4.3E-07	
22	PM2,5-PM10	Nickel Concentrate	26164	10000003	1.1E-03	

Figure 31. LCA Stressors matrix for mining and beneficiation



23	Water, Surface water consumption/resour	Nickel Matte	3048	10000002	9.5E-03
24	Water, river/resource/in water/m3	Nickel Matte	799	10000002	3.4E-03
25	Water, process, surface/resource/unspeci	Nickel Matte	27375	10000002	1.7E-01
26	Antimony/air/low population density/kg	Nickel Matte	45	10000002	9.9E-08
27	Cobalt/air/low population density/kg	Nickel Matte	151	10000002	2.4E-05
28	Copper to air	Nickel Matte	157	10000002	2.6E-04
29	Lead to air	Nickel Matte	299	10000002	1.7E-04
30	Manganese to air	Nickel Matte	311	10000002	1.3E-05
31	Mercury to air	Nickel Matte	316	10000002	8.0E-07
32	Nickel to air	Nickel Matte	27448	10000002	5.0E-04
33	Zinc to air	Nickel Matte	27468	10000002	4.5E-05
34	Carbondioxide	Nickel Matte	15521	10000002	9.0E-01
35	Nitrogen oxides to air	Nickel Matte	383	10000002	1.4E-03
36	Nitrogen dioxide	Nickel Matte	14786	10000002	5.2E-04
37	Sulphur to air	Nickel Matte	23027	10000002	2.8E-05
38	Sulphur dioxide	Nickel Matte	506	10000002	2.4E+00
39	Sulfuric acid/air/unspecified/kg	Nickel Matte	24128	10000002	1.7E-02
40	Methane	Nickel Matte	26551	10000002	4.1E-05
41	Cadmium to air	Nickel Matte	27443	10000002	5.8E-06
42	Chromium to air	Nickel Matte	144	10000002	2.8E-06
43	Carbon monoxide	Nickel Matte	25996	10000002	4.5E-03
44	NMVOC	Nickel Matte	26219	10000002	3.0E-05
45	PM10	Nickel Matte	26581	10000002	1.2E-02
46	PM2,5-PM10	Nickel Matte	26164	10000002	1.0E-02
47	Arsenic/air/low population density/kg	Nickel Matte	52	10000002	2.0E-05

Figure 32. LCA Stressors matrix for primary extraction



48	Water, Surface water consumption/resour	Nickel Sulphate	3048	10000001	7.3E-01
49	Water, river/resource/in water/m3	Nickel Sulphate	799	10000001	2.2E-02
50	Water, process, surface/resource/unspeci	Nickel Sulphate	27375	10000001	1.8E+00
51	Cobalt-57/air/low population density, lon	Nickel Sulphate	23745	10000001	1.9E-05
52	Copper/air/unspecified/kg	Nickel Sulphate	160	10000001	9.3E-04
53	Nickel/air/unspecified/kg	Nickel Sulphate	373	10000001	5.0E-04
54	Carbon dioxide/air/unspecified/kg	Nickel Sulphate	15521	10000001	3.4E-01
55	Nitrogen oxides/air/unspecified/kg	Nickel Sulphate	383	10000001	3.4E-05
56	Nitrogen dioxide/air/unspecified/kg	Nickel Sulphate	14786	10000001	5.2E-05
57	Sulfur dioxide/air/unspecified/kg	Nickel Sulphate	506	10000001	5.8E-02
58	Sulfuric acid/air/unspecified/kg	Nickel Sulphate	24128	10000001	4.1E-03
59	Methane	Nickel Sulphate	26551	10000001	9.0E-07
60	Carbon Monoxide/air/unspecified/kg	Nickel Sulphate	13377	10000001	1.4E-03
61	NMVOC, non-methane volatile organic cor	Nickel Sulphate	368	10000001	1.9E-06
62	Particulates, > 2.5 um, and < 10um/air/nor	Nickel Sulphate	26164	10000001	5.4E-03

Figure 33. LCA Stressors matrix for refining

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