Summary Life Cycle Assessment Report: Nickel Sulphate Hexahydrate

Reference year: 2017

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List of Acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
ASTM	the American Society for Testing and Materials
BWC	Blue Water Consumption
CML	Centre of Environmental Science at Leiden
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GB/T	Guobiao standards or GB standards
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
PEF	Product Environmental Footprint
POCP	Photochemical Ozone Creation Potential
VOC	Volatile Organic Compound

Glossary

Life Cycle

A view of a product system as “consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal” ([1], section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” ([1], section 3.2)

Life Cycle Inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” ([1], section 3.3)

Life Cycle Impact Assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” ([1], section 3.4)

Life cycle Interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” ([1], section 3.5)

Functional Unit

“Quantified performance of a product system for use as a reference unit” ([1], section 3.20)

Allocation

“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” ([1], section 3.17)

Closed-Loop and Open-Loop Allocation of Recycled Material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.”

([2], section 4.3.4.3.3)

Foreground System

"Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study." [3] [p.97]. This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background System

"Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good…." [3] [p.97-98] As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" ([2], section 3.45).

1. Goal of the Study

About 70% of the nickel which is produced is still used to manufacture stainless steels [4]. As a result of changes in manufacturing technology, choice of raw materials, improved efficiencies and rationalisation, the global steel sector continues to update LCI database for stainless and carbon steel products. This, in turn, requires the need for rigorous nickel LCI datasets. However, the forecasted dominant driver of nickel demand growth in the future is in the form of lithium-ion (Li-ion) batteries, which have become the technology of choice for core automotive and energy storage system (ESS) applications. Nickel-rich Li-ion batteries show a superior energy density to other types, and lower metal cost to higher cobalt containing technology, making them the technology of choice for use in plug-in electric vehicles (EVs). Not all nickel is classified as suitable for use in Li-ion batteries, where nickel itself must be in a chemical compound form: nickel sulphate hexahydrate ($NiSO_4 \cdot 6H_2O$) for use in cathode precursor manufacturing[1].

Between 2018 and 2019, the Nickel Institute conducted an update of the Life Cycle Assessment (LCA) on nickel products Class 1 nickel and ferronickel, and included the development of a nickel sulphate hexahydrate dataset in an effort to provide its stakeholders with up-to-date, reliable life cycle inventory (LCI) data. The datasets were based on the input from the Nickel Institute members for the year 2017 representing 52% of the global production of Class 1 nickel; 47% of the global production of ferronickel and 15% of the global production of nickel sulphate hexahydrate. The study focused on quantifying the environmental impacts of the cradle to gate production of nickel products and was finalised in 2020. The LCI dataset developed for nickel sulphate hexahydrate represented three different types of feedstock routes, according to the contributing production volumes of these individual companies to the study. In 2021, the European Commission published a report done by Roskill indicating the current and outlook of nickel sulphate production from various feedstock. The goal of this study is therefore to update and assess the life cycle environmental profile for the global production of nickel sulphate hexahydrate according to the actual market mix production from the various feedstock materials[1].

The results generated from this study will inform the Nickel Institute's members and stakeholders about the in- and outputs and related environmental impacts of the production of the nickel sulphate hexahydrate.

The target audience for this study incudes the Nickel Institute; nickel producers; first and end users (customers), legislators, academia, LCA practitioners, non-governmental organisations (NGOs), and in view of the growing public debate around energy and climate change financial stakeholders such as e.g. investors, the broad media landscape and the public.

It is acknowledged that the data provided might be used by others for comparative assertions. Such comparisons should only be made on a product system basis and must be carried out in accordance with the ISO 14040 [1] and the ISO 14044 [2] standards, including an additional critical review by a panel. This report is not conformed to ISO 14040, ISO 14044 and ISO/TS 14071 and serves only as a summary of the life cycle assessment conduct. The methodology is conformed to the main study[2].

[1] Study on future demand and supply security of nickel for electric vehicle batteries; Roskill for the JRC; Luxembourg; 2021
[2] Life Cycle Assessment of Nickel Products; Sphera for the Nickel Institute; May 2020

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product System and Functional Unit

Nickel products fall within the following categories:

- Class 1 (refined) nickel: containing >99.8% nickel according to the American Society for Testing and Materials (ASTM) specification B39-79 (2013) or GB/T 6516-2010 (Guobiao or GB standards[3]). **Nickel** metal is studied without distinction between specific products within the general category, such as nickel squares, powder, and briquettes [5].
- Class 2 (charge) nickel: several nickel intermediate products containing <99.8% nickel, such as nickel oxide sinter, ferronickel or nickel pig iron. **Ferronickel** (27% Nickel metal content, based on the volumes considered in this study) falls under Class 2 nickel as well as other products such as nickel oxides and nickel pig iron [5].
- Chemicals: **Nickel sulphate** along with nickel chlorides, nickel carbonates, and other nickel salts fall into this category

Primary nickel is produced from either oxidic (lateritic) or sulphidic ore. Class 1 nickel can be produced from both ore types and can be produced from either pyrometallurgical or hydrometallurgical processes. It is also a by-product from precious group metals (PGM) production. Secondary production, or a production route by recycling, is not considered in this study since most recovery of nickel occurs in its alloy state outside the nickel industry, combined with other metals. For example, most of nickel recycling takes place in stainless steel mills. While the majority of nickel and ferronickel is used for the production of nickel-containing alloys, approximately 15% of all nickel goes into the production of nickel chemicals, of which nickel sulphate is one of the most widely used [6]. There are different ways of producing nickel sulphate. It is obtained from nickel matte used in the production of metallic nickel. Nickel sulphate is also produced as a secondary product from ores mined primarily for their content of copper and other metals such as platinum group metals. The nickel present in these ores is recovered as nickel sulphate where it occurs as impurity in the spent electrolyte during refining. Typically nickel sulphate is produced as the hexahydrate [7]. Its most important use is as a key constituent of solutions in nickel plating baths as well as cathode material in lithium-ion batteries.

This study focuses on the *nickel sulphate hexahydrate* (referred to as nickel sulphate in this report).

Results are presented considering market mix in 2020.

[3] Chinese national standards issued by the Standardization Administration of China (SAC),

2.2. Product Function(s) and Functional Unit

The functional unit is the reference value for which the results of the study are calculated. Generally, a functional unit should reflect the function provided by the product being assessed, and enables the system inputs and outputs to be quantified and normalised. Nickel sulphate hexahydrate with chemical formula, $NiSO_4 \cdot 6H_2O$, has a mass content of 22%.

Consequently, the following mass-based functional units and reference flows have been designated for this study:

- 1 kg of nickel sulphate (22% nickel content)

This functional unit is consistent with the study's goals to calculate the environmental impact of nickel sulphate and providing data to LCA practitioners and other stakeholders, which is often provided on a mass basis with a cradle-to-gate system boundary. No alternative product systems or functional units are considered, such as those related to the generation of by-products (precious metals and other base metals) from the production of nickel products. These by-products are included in the system boundary, however have been treated using the allocation approach recommended as documented in the main report.

2.3. System Boundary

This study considers the cradle-to-gate production of nickel products, meaning that it considers impacts associated with the extraction of resources from nature (through mining) through to the point at which the refined product leaves the factory gate. For the primary route, the impact associated with the mining of nickel ore is considered. This is considered to be the appropriate choice of the system boundaries, as nickel products serve as intermediates that enter many different product life cycles. Figure 2-1 (depicted by the red border) shows the system boundary considered in this study.

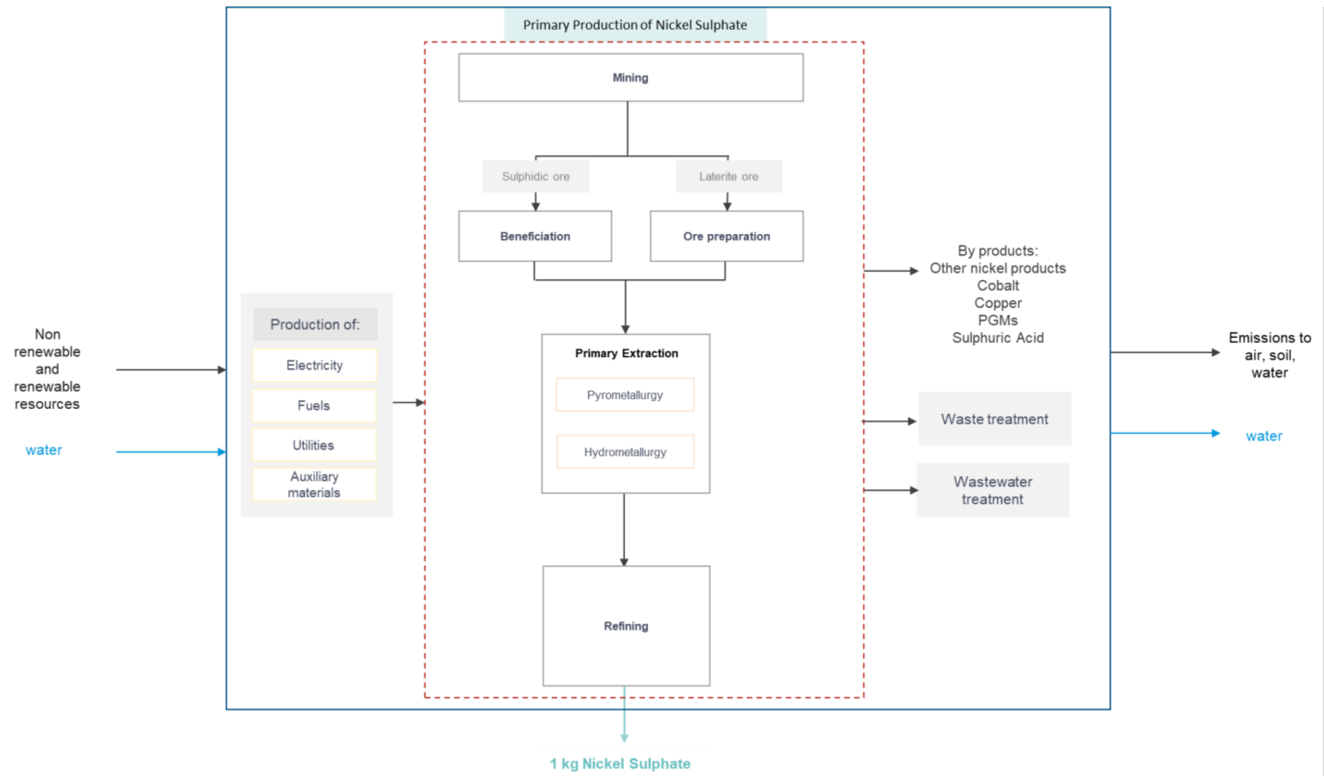

Figure 2-1: System boundary

Table 2-1 shows the major process steps considered within the system boundaries. Not all processes will apply to every manufacturer or processing route.

Table 2-1: Processes considered within the system boundary

Included	Excluded
✓ Mining (underground or open cast / surface including overburden and waste rock) ✓ Beneficiation ✓ Ore preparation ✓ Primary extraction (pyrometallurgical and hydrometallurgical processes) - to matte, mixed sulphides, ferronickel, and nickel oxide, including processes such as leaching and separation, reductive calcination, smelting, converting, etc. ✓ Refining - to the final nickel products, including processes such as leaching, electro-refining, volatizing, etc ✓ Transport of ore, concentrates, mattes ✓ All associated energy and fuels ✓ Ancillary / auxiliary materials used on site ✓ All relevant water inputs and outputs ✓ On-site (direct) emissions to air ✓ On-site water treatment and water emissions ✓ Overburden, tailings and other mining wastes that are deposited onsite ✓ Wastes and waste water treated onsite.	× Refining processes associated with nickel sulphate as a by-product from PGM and copper production routes × Secondary production (recycling) of nickel products × Effect of potential volume of acid mine drainage from waste rock × Packaging × Transport of fuels / ancillary / auxiliary materials to site × Transport to customer × Transport of waste × Production of capital equipment and infrastructure

By-products of the production of nickel products such as other base metals, metal compounds (excluding nickel sulphate, which is a product under study) and precious metals are part of the scope of this study. These by-products have been treated using the recommended allocation approach documented in the main study. Data on the volume of overburden or waste rock generated was collected, however due to the lack of information, the potential of acid mine drainage from this waste rock was not considered.

Packaging used for transporting products to customer is excluded. Assessments in past data collections have shown that packaging is not expected to have a significant effect on the results and therefore can be excluded according to the cut off criteria defined in the main study.

Transport of fuels / ancillary / auxiliary materials is excluded as it is expected to be significantly smaller than the impacts of transport of ore, concentrates and mattes. Production and maintenance of capital goods are also excluded from the study, unless they are included in some background datasets, in which they are relevant (e.g. renewable energy). It is expected that these impacts are negligible compared to the impacts associated with running the equipment over its operational lifetime. As this is a cradle-to-gate study, transport to the customer and transport of waste outside the site lies outside the system boundary.

2.3.1. Time Coverage

The intended time reference for the study is 2017 and data collected from the Nickel Institute member companies participating in the study relate to this year. The dataset is modelled according to the market mix as it was in 2020[1]. The results of the study are relevant for 2020 and are expected to be relevant until there is a significant change in e.g. ore geology and mineralogy, the production mix (viz. geographical distribution of production volumes), energy mix or manufacturing technology.

2.3.2. Technology Coverage

This study assesses the cradle-to-gate impacts of the production of nickel sulphate based on a global production and technology mix. It considers surface and underground mining of both sulphidic and laterite ore as well as both pyrometallurgical and hydrometallurgical processing routes. Production data were gathered from the Nickel Institute's participating members to ensure that the model used to assess the environmental impacts of the nickel products under study is technologically representative for each stage of each of the investigated production processes.

The production processes include the unit processes as defined in section 3.

2.3.3. Geographical Coverage

The geographical coverage of this study considers the global production of nickel products. 52% (556 000 tons) of globally produced Class 1 nickel (2011: 52%), 47% (734 000 tons) of globally produced ferronickel (2011: 40%) and 15% (105 000 tons) of globally produced nickel sulphate are represented in this study.

The nickel producing regions are shown in Figure 2-2 [8]. This map represents the breakdown for primary nickel production and includes all nickel products for the reference year 2017.

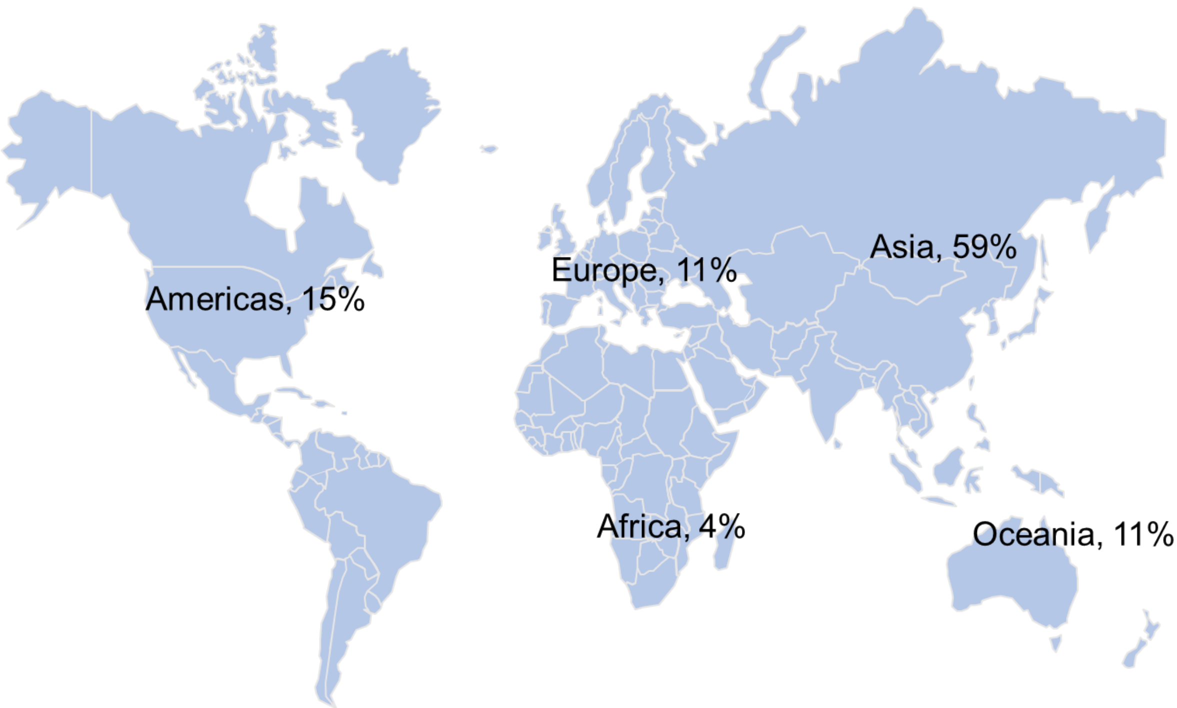

Figure 2-2: Breakdown of primary nickel production (all nickel products) across regions

This study covers all regions except Africa and China, which is a significant part of production in Asia. According to INSG data, China represents around 31% of global nickel production and is not represented in these results due to lack of availability of data (providers). Table 2-2 provides an indication of the operations taking place in each country.

Table 2-2: Location of operations per country

Company	Site/Division	Location	Product	Ore Type	Mine Type
Anglo American	Barro Alto	Brazil	FeNi	Laterite	Surface
	Codemin	Brazil	FeNi	Laterite	Surface
	Rustenberg	South Africa	Nickel	Sulphidic	Mixed
South 32	Cerro Matoso	Columbia	FeNi	Laterite	Surface
Sherritt		Cuba	Mixed sulphides	Laterite	Surface
		Canada	Nickel		(Plant)
Eramet	Doniambo	New Caledonia	FeNi	Laterite	Surface
	Sandouville	France	Nickel	Laterite	(Plant)
Nornickel	Harjavalta	Finland	Nickel Nickel sulphate	Sulphidic	Mixed
	Polar and Kola	Russia	Nickel	Sulphidic	Mixed
Sumitomo	Niihama	Japan	Nickel	Sulphidic	Mixed
	Niihama	Japan	Nickel sulphate	Sulphidic	Mixed
	Harima	Japan	Nickel sulphate	Sulphidic	Mixed
	Coral Bay Nickel Corporation	Phillipines	Mixed sulphides	Laterite	
	Taganito HPAL Nickel Corporation	Phillipines	Mixed sulphides	Laterite	
	Hyuga	Japan	FeNi	Laterite	Surface
Vale	Sudbury	Canada	Nickel	Sulphidic	Underground
	Voisey Bay	Canada	Nickel	Sulphidic	Surface
	Clydach	United Kingdom	Nickel	Sulphidic	(Plant)
	PT Indonesia	Indonesia	Nickel matte	Laterite	Surface
	Brazil	Brazil	FeNi	Laterite	Surface
	Matsusaka	Japan	Nickel oxide	Intermediate product	
Glencore	Sudbury/Raglan	Canada	Nickel	Sulphidic	Underground
	Koniambo	New Caledonia	FeNi	Laterite	Surface
	Nikkelverk	Norway	Nickel	Sulphidic	(Plant)
	Murrin Murrin	Australia	Nickel	Laterite	Surface
Umicore	Olen	Belgium	Nickel sulphate	Sulphidic	Plant

2.4. Impact Categories

The impact categories assessed in this report are consistent with those in the main study[2]. Any justification for inclusion or exclusion is outlined in that report.

Impact categories used in this study for the nickel industry are shown in **Table 2-3**.

Table 2-3: Impact categories considered for assessment

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP100)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	[9]
Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg PO_4^{3-} equivalent	[10]
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	[10]
Photochemical Ozone Creation Potential (POCP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg C_2H_4 equivalent	[10]

Table 2-4: Other environmental indicators considered for assessment

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	[10]
Blue Water Consumption	Freshwater that leaves the watershed is considered consumed.	kg	[11]

The LCA model was created using the GaBi 10 Software system for life cycle engineering, developed by Sphera. The GaBi 2020 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

3. Life Cycle Inventory Analysis

3.1. Production of Nickel Sulphate

3.1.1. Description of unit processes

For the production of nickel, only the primary production route from ores is considered since the secondary route considers the recovery of nickel in alloy form and takes place outside the nickel industry in stainless steel plants.

Mining

Nickel is produced from two very different ores, lateritic and sulphidic. Lateritic ores are normally found in tropical climates where weathering, with time, extracts and deposits the ore in layers at varying depths below the surface. Lateritic ores are excavated using large earth-moving equipment and are screened to remove boulders. The metal bearing minerals are usually of oxidic nature. Sulphidic ores are often found in conjunction with copper-bearing ores and are often mined from underground [12]. The metal bearing minerals are usually of sulfidic nature. The nickel mining stage of nickel production includes all processes to extract nickel ore up to the point of delivery to beneficiation or ore preparation. It is modelled as a "black box" with all energy and material inputs contributing to total the mining operations at a site.

Beneficiation and Ore Preparation

After the ore has been mined, it is then either crushed, screened and dried (ore preparation), or undergoes beneficiation where the ore is crushed, ground and undergoes flotation or magnetic separation to obtain a nickel concentrate. Beneficiation may be nickel only (produces nickel containing concentrates) or shared (produces nickel, copper and precious metals containing concentrates). In general, lateritic ore undergoes ore preparation and sulphidic ore undergoes beneficiation. Lateritic ore generally has high moisture content [12]. The principal component of the ore preparation processes is therefore drying of ore. Approximately half of the total moisture content of the oxidic ore is removed during ore preparation. In specific cases lateritic ore can undergo processing which results in an increased concentration of the nickel in the ore, beyond that which can be obtained through drying. However, these processes are distinct from the processes that occur during the beneficiation of sulphidic ore. Within this study, all processing of lateritic ore prior to primary extraction is grouped under "ore preparation" while the term "beneficiation" refers to the production of nickel concentrate from sulphidic ores only. Results presented in this study aggregate the two processes to avoid disclosure of company specific data in the case of Class 1 nickel and nickel sulphate. The individual beneficiation and ore preparation processes are modelled as a "black box" with all energy and material inputs contributing to the total process. Typically, producers are not able to separate data such as electricity for pumping, or fuels for vehicles used for tailings and these are also included in this "black box" data.

Primary Extraction

Primary extraction involves the conversion of prepared ore and nickel concentrate into nickel matte, nickel oxide, ferronickel, nickel cobalt intermediates, and other nickel and non-nickel co-products. There are four main process routes for primary extraction;

- Hydrometallurgical extraction from lateritic ore

- Hydrometallurgical extraction from sulphidic ore
- Pyrometallurgical extraction from lateritic ore
- Pyrometallurgical extraction from sulphidic ore

Sulphidic ores are typically processed using the pyrometallurgical process of flash smelting. Electric smelting can also be used for more complex ore types, which requires a roasting step before. The reactions which take place are exothermic, therefore providing enough heat to smelt the concentrate. The furnace matte that is produced still contains iron and sulphur and therefore is fed to a converter where these components are oxidised. Oxides form a molten slag which is sent for nickel recovery before discarding. Lateritic ores are typically processed in the pyrometallurgical process in electric furnaces since they do not contain enough energy (i.e. in the form of oxidisable metallic sulphides) to provide the heat to smelt. Some laterite smelters add sulphur to the furnace to produce a matte for processing. Most laterite furnaces are used to produce ferronickel. Laterite ores are also processed using hydrometallurgy based on ammonia or sulphuric acid leaching [12]. High Pressure Acid Leaching (HPAL) currently represents around 20% of nickel supply and is typically the solution for the lower grade lateritic ores. The core operation of HPAL is reaction of a slurry with sulphuric acid in an autoclave to leach nickel and cobalt, on average at 255°C and 4500kPa. Counter-current decantation wash then separates out the residue (mostly iron oxide), before acid neutralisation, using limestone, and sulphide precipitation [13]. Typically a mixed nickel-cobalt sulphide is produced for further refining.

Results presented in this study aggregate the inventory and impacts for primary extraction, in the case of the production of Class 1 Nickel, from both routes. Furnaces and the various steps making up the HPAL is modelled as a “black box” with all energy and material inputs contributing to total process (i.e. from receipt of concentrate to production of the nickel matte or mixed sulphide).

Refining

Various processes are used to refine nickel matte or mixed sulphides. Use of electrical cells equipped with inert cathodes is the most common technology for nickel refining. Electrowinning, in which nickel is removed from solution in cells equipped with inert anodes, is also common. Sulphuric acid solutions or, less commonly, chloride electrolytes are used [12]. Refining often involves the separation of nickel from other metals, and results in diverse nickel and other metal and non-metal by-products. It is modelled as a “black box” with all energy and material inputs contributing to total the refining process (i.e. from the receipt of the nickel matte / mixed sulphides to the production of refined nickel).

Nickel sulphate is typically produced from the leaching of nickel matte from the primary production route. It is also produced as a secondary product from ores mined primarily for their content of copper and other metals such as PGMs. The nickel present in these ores is recovered as nickel sulphate as a product of the leaching process (refining processes). A raw nickel solution is produced from the leaching process which then undergoes solvent extraction to reduce impurities and produce a pure nickel solution. This pure nickel solution is either fed to a reduction or electrowinning process to produce the nickel sulphate. In other cases, nickel is also leached from nickel containing residues which are formed as a by-product during the leaching from the nickel matte such as copper sulphide. The nickel is recovered to copper anodes and purified in copper electrolysis. The nickel is then recovered as a crude nickel sulphate (nickel sulphate monohydrate) before being returned to the leaching process and fed with the nickel matte. Other leaching processes using secondary raw materials (sub materials or raw materials produced as by-products with lower metal contents) are also used. These materials are first dissolved in sulphuric acid before the resulting solution is purified by neutralisation and solvent extraction. Nickel sulphate is produced following further refining [7].

Another major route is the production of $NiSO_4 \bullet 6H_2O$ via nickel metal / nickel powder. The involves dissolving nickel in sulphuric acid and concentrating the solution to precipitate $NiSO_4 \bullet 7H_2O$ which on heating forms the commercial crystalline $NiSO_4 \cdot 6H_2O$.[4] The nickel metal raw materials considered here is the global average out of the nickel LCA study. The production of $NiSO_4 \cdot 6H_2O$ is based on a stochiometric calculation.

The refining process for nickel sulphate includes all the various processes from the point of acceptance of the nickel matte or other raw materials into the leaching process until the production of the nickel sulphate.

Water and waste water treatment

Water data was collected for the site as a whole, however only included at a process level where water forms part of the process / product and influences the mass balance, i.e. in hydrometallurgical and the refining processes. This is reflected in the gate to gate data presented for each product considered in the sections below. Data for the waste water treatment plants was collected and focused on emissions to water. Therefore, all emissions to water would be reported under this process, for discharges. From the waste water treatment plant water is either recycled or discharged. Water and waste water treatment plants are modelled case by case for each company depending on their process and provision of data, as there is no general process flow, but a general modelling approach as shown in the basic flow diagram in, for example, Figure 3-1 is undertaken. In some cases, water is not sent to onsite waste water treatment plants but to municipal treatment plants.

Transport

Transport is only considered for the movement of products between different locations (mainly different countries or for the movement of third party raw materials). Where products move within the same site or from processes on the same site, fuel consumption associated with this transport is already included in fuel data collected. The differentiator between these transports is that where transport is considered, this would be out of the “ownership” of the producer under study.

3.1.2. Overview of Product System

Figure 3-1 shows the overall process flow for the production of nickel sulphate with key inputs and outputs. The upstream for the raw materials into the refining step encompass both the pyrometallurgical and hydrometallurgical routes. The detailed data for each unit process (and auxiliary processes such as waste water treatment) is given in section 3.1.3.

[4] https://pubchem.ncbi.nlm.nih.gov/compound/Nickel-sulfate#section=Consumer-Uses

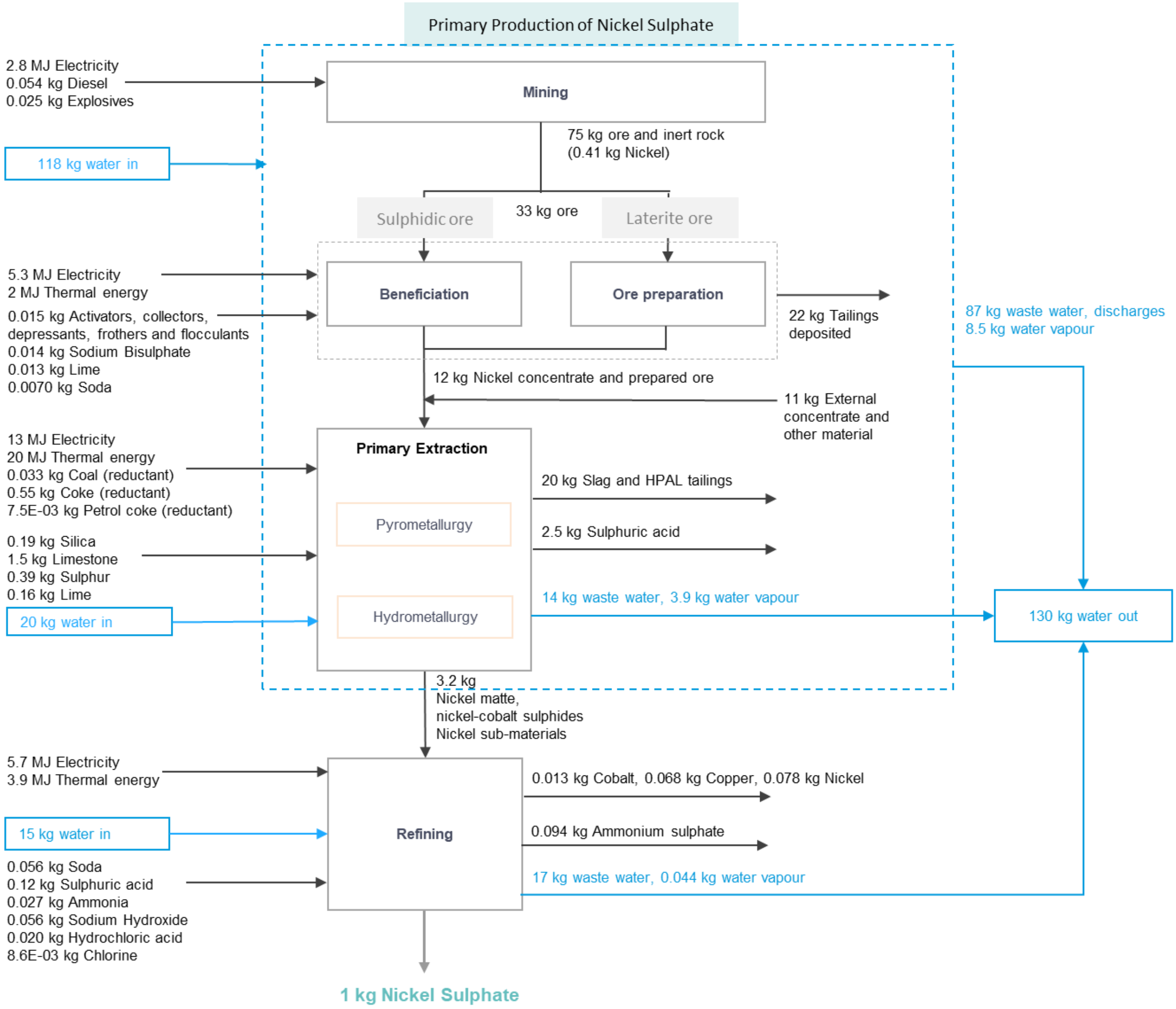

Figure 3-1: Overview of Nickel Sulphate Product System

3.1.3. Gate to gate data

The average gate to gate data is presented here for all unit processes for which data was collected. The gate to gate data is generated for, and refers to, the production of 1 kg nickel sulphate weighted according to the market mix of various feed materials. In general data was disaggregated for all unit processes accordingly, and is all measured. Only data associated with combustion processes are calculated. Where specific inputs or outputs were deemed to be company specific, these were aggregated into more generic and equivalent flows or deleted where the mass was insignificant (only for the case of presentation in this report, and not in the model). For example, the three main nickel raw materials into the refining process represent the feeds of individual companies and have therefore been combined. In general, water data shall be assessed cautiously and should be assessed in total rather than at a unit process level. Data should be viewed in context of the flow diagram presented in Figure 3-1.

Table 3-1: Gate to gate data for the mining process for the production of Nickel Sulphate

Inputs	Unit	Quantity
Air	kg	6.24E-03
Cobalt	**kg**	**0.010**
Copper	**kg**	**0.31**
Diesel	kg	0.054
Explosives	kg	0.025
Gasoline	kg	1.65E-05
Gold	kg	5.69E-07
Inert rock	**kg**	**45**
Nickel	**kg**	**0.41**
Nickel ore	**kg**	**29**
Palladium	kg	7.06E-05
Platinum	kg	2.32E-05
Rhodium	kg	5.71E-07
Iron	kg	0.064
Lubricant	kg	0.010
Outputs	**Unit**	**Quantity**
Overburden (deposited)	kg	35
Carbon dioxide to air	kg	0.18
Nitrogen oxides to air	kg	2.71E-04
Nitrogen dioxide to air	kg	1.53E-04
Sulphur dioxide to air	kg	1.72E-04
Methane to air	kg	2.67E-04
Hazardous waste for incineration	kg	5.53E-05
Non-hazardous waste for land-filling	kg	4.70E-03
Waste for recovery (unspecific)	kg	9.09E-04
Water (waste water; treated)	kg	1.4
Nickel ore mined	**kg**	**33**
Waste rock	kg	5.5
Carbon monoxide to air	kg	2.20E-04
NMVOC (unspecified) to air	kg	1.20E-05
Dust (PM10) to air	kg	8.56E-05
Dust (PM2.5 - PM10) to air	kg	6.44E-06
Non-hazardous waste for incineration	kg	7.84E-05
Ore Stockpile (deposited)	kg	0.015
ELECTRICITY AND ENERGY*		
Inputs	**Unit**	**Quantity**
Electricity	MJ	2.8
Thermal energy from LPG	MJ	5.44E-05

*Energy removed due to confidentiality

Table 3-2: Gate to Gate data for the beneficiation and ore preparation processes for the production of Nickel Sulphate

Inputs	Unit	Quantity
Diesel	kg	4.31E-03
Flocculant	kg	0.014
Gasoline	kg	8.67E-06
Grinding media	kg	0.023
Internal recovery	kg	0.17
Nickel ore mined	**kg**	**33**
Sodium bisulphite	kg	0.014
Sulphuric acid	kg	1.33E-04
Nitric acid	kg	4.19E-05
Soda	kg	7.04E-03
Phosphates	kg	7.51E-05
Lubricant	kg	4.17E-04
Lime	kg	0.013
Ferrous sulphate	kg	4.33E-07
Activator	kg	3.88E-05
Antiscalant	kg	1.13E-06
Depressant	kg	1.08E-03
Frother	kg	4.96E-04
Outputs	**Unit**	**Quantity**
Nickel concentrate and prepared ore	**kg**	**12**
Carbon dioxide to air	kg	0.092
Nitrogen oxides to air	kg	1.24E-04
Sulphur dioxide to air	kg	1.15E-04
Water vapour	kg	3.03E-03
Methane to air	kg	7.64E-06
Hazardous waste for incineration	kg	7.44E-07
Non-hazardous waste for land-filling	kg	1.6
Waste for recovery (unspecific)	kg	1.2
Carbon monoxide to air	kg	1.86E-05
NMVOC (unspecified) to air	kg	5.17E-06
Dust (PM10) to air	kg	1.09E-05
Dust (PM2.5 - PM10) to air	kg	3.67E-06
Dust (unspecified) to air	kg	3.86E-04
Tailings	kg	22
Non-hazardous waste for incineration	kg	6.68E-04
ELECTRICITY AND ENERGY		
Inputs	**Unit**	**Quantity**
Electricity	MJ	5.3
Thermal energy from hard coal	MJ	0.56
Thermal energy from heavy fuel oil	MJ	0.12
Thermal energy from LPG	MJ	1.50E-05
Thermal energy from natural gas	MJ	1.4

Table 3-3: Gate to Gate data for the primary extraction processes for the production of Nickel Sulphate

Inputs	Unit	Quantity
Ammonia	kg	1.4E-04
Collector	kg	2.5E-04
Diesel	kg	1.6E-03
Electrodes	kg	3.1E-03
External concentrate and other material	**kg**	**11**
Gasoline	kg	0.043
Graphite	kg	7.4E-05
Ground water	kg	1.2
Coal	kg	0.033
Hydrochloric acid (100%)	kg	0.019
Internal recovery	kg	0.073
Lake water	kg	2.8
Limestone	kg	1.5
Nickel concentrate and prepared ore	**kg**	**12**
Oxygen gaseous	kg	3.4
Pellet feed	kg	0.025
Petrol coke	kg	7.5E-03
Rain water	kg	7.9E-03
River water	kg	15
Sand	kg	0.74
Slag (containing Ni)	kg	0.12
Sulphur	kg	0.39
Nitric acid	kg	1.1E-07
Soda	kg	0.11
Lubricant	kg	3.5E-04
Lime	kg	0.16
Coke	kg	0.55
Ferric chloride	kg	0.053
Hydrogen peroxide	kg	4.3E-04
Sodium hydroxide	kg	0.020
Silica	kg	0.19
Process water	kg	1.9
Water kept in loop (internally recycled)	kg	3.9
Iron scrap	kg	0.59
Ferrous sulphate	kg	5.3E-05
Hydrogen sulphide	kg	5.3E-03
Nitrogen liquid	kg	7.2E-05
Oxygen liquid	kg	4.7E-05
Used oil	kg	1.2E-04
Outputs	**Unit**	**Quantity**
Nickel matte, nickel-cobalt sulphide and nickel sub materials	**kg**	**3.2**
Sulphuric acid	kg	2.5

Internal recovery (Ni content)	kg	0.13
Water (waste water; untreated)	kg	14
Slag and HPAL Tailings	kg	20
Antimony to air	kg	5.2E-07
Cobalt to air	kg	8.9E-06
Copper to air	kg	9.9E-05
Lead to air	kg	6.8E-05
Manganese to air	kg	5.0E-06
Mercury to air	kg	7.3E-07
Nickel to air	kg	1.8E-04
Zinc to air	kg	1.8E-05
Carbon dioxide to air	kg	3.2
Nitrogen oxides to air	kg	7.5E-03
Nitrogen dioxide to air	kg	1.9E-04
Sulphur to air	kg	9.7E-06
Sulphur dioxide to air	kg	0.90
Sulphuric acid to air	kg	6.1E-03
Water vapour	kg	3.9
Methane to air	kg	2.2E-04
Hazardous waste for incineration	kg	4.7E-05
Non-hazardous waste for land-filling	kg	0.022
Waste for recovery (unspecific)	kg	1.0E-04
Cadmium to air	kg	2.4E-06
Chromium to air	kg	1.2E-06
Carbon monoxide to air	kg	3.4E-03
NMVOC (unspecified) to air	kg	1.7E-04
Dust (> PM10) to air	kg	2.4E-05
Dust (PM10) to air	kg	5.0E-03
Dust (PM2.5 - PM10) to air	kg	3.8E-03
Hydrochloric acid to air	kg	3.1E-05
Arsenic to air	kg	8.7E-06
ELECTRICITY AND ENERGY		
Inputs	**Unit**	**Quantity**
Electricity	MJ	13
Thermal energy from heavy fuel oil	MJ	8.8
Thermal energy from light fuel oil	MJ	0.024
Thermal energy from LPG	MJ	0.062
Thermal energy from natural gas	MJ	11

Table 3-4: Gate to Gate data for the refining process for the production of Nickel Sulphate

Inputs	Unit	Quantity
Air	kg	5.1E-05
Ammonia	kg	0.027
Chlorine	kg	8.6E-03
Diesel	kg	4.7E-05

Electrodes	kg	1.2E-03
Flocculant	kg	1.2E-04
Gasoline	kg	8.6E-06
Ground water	kg	0.26
Hydrochloric acid	kg	0.020
Hydrogen	kg	1.5E-03
Internal recovery	kg	1.2E-03
Nickel matte, nickel-cobalt sulphide and nickel sub materials	**kg**	**3.2**
Nitrogen gaseous	kg	0.019
Oxygen gaseous	kg	0.15
Rain water	kg	0.29
River water	kg	7.9
Sulphur dioxide	kg	0.012
Sulphuric acid	kg	0.12
Soda	kg	0.056
Phosphates	kg	4.4E-04
Lubricant	kg	6.9E-05
Lime	kg	0.013
Hydrogen peroxide	kg	5.3E-03
Sodium hydroxide	kg	0.056
Silica	kg	1.0E-05
Process water	kg	6.6
Sodium chloride	kg	1.9E-04
Sodium Naphthalenesulfonate	kg	1.0E-04
Sodium hydrogen sulphite	kg	4.9E-04
Hydrogen sulphide	kg	2.4E-04
Oxygen liquid	kg	3.9E-03
Sodium thiosulfate	kg	1.0E-04
Sodium hydrogen fluoride	kg	4.7E-04
Formaldehyde	kg	1.6E-04
Outputs	**Unit**	**Quantity**
Cobalt	kg	0.013
Copper	kg	0.068
Nickel	kg	0.078
Sodium sulphate	kg	9.2E-03
Internal recovery (Ni content)	kg	0.16
Water kept in loop (internally recycled)	kg	7.5
Water (waste water; untreated)	kg	9.4
Antimony to air	kg	1.3E-09
Cobalt to air	kg	6.8E-06
Copper to air	kg	3.4E-04
Lead to air	kg	1.6E-07
Manganese to air	kg	7.1E-09
Mercury to air	kg	1.5E-10
Nickel to air	kg	1.8E-04

Zinc to air	kg	4.3E-08
Ammonia to air	kg	3.4E-06
Carbon dioxide to air	kg	0.20
Nitrogen oxides to air	kg	1.3E-04
Nitrogen dioxide to air	kg	1.7E-05
Sulphur dioxide to air	kg	0.022
Sulphuric acid to air	kg	1.5E-03
Water vapour	kg	0.044
Methane to air	kg	6.3E-06
Used air	kg	0.055
Processed water to river	kg	0.086
Hazardous waste for incineration	kg	1.7E-04
Non-hazardous waste for land-filling	kg	8.9E-04
Waste for recovery (unspecific)	kg	1.4E-04
Copper sulphide	kg	1.0E-02
Ammonium sulphate	kg	0.094
Nickel sulphate	**kg**	**1.00**
PGM containing material	kg	0.032
Cadmium to air	kg	1.6E-09
Chromium to air	kg	1.2E-08
Carbon monoxide to air	kg	5.4E-04
Chlorine to air	kg	2.4E-05
NMVOC (unspecified) to air	kg	1.3E-05
Dust (PM10) to air	kg	8.9E-06
Dust (PM2.5 - PM10) to air	kg	1.9E-03
Dust (PM2.5) to air	kg	2.0E-07
Arsenic to air	kg	6.4E-07
Non-hazardous waste for incineration	kg	8.3E-05
Cobalt sulphate	kg	1.2E-04
Cobalt chloride (CoCl2)	kg	1.9E-05
Other nickel products	kg	1.4E-03
Zinc sulphide	kg	2.3E-04
External recovery	kg	2.0E-03

ELECTRICITY AND ENERGY		
Inputs	**Unit**	**Quantity**
Electricity	MJ	5.7
Steam	MJ	4.3
Thermal energy from hard coal	MJ	0.26
Thermal energy from heavy fuel oil	MJ	0.25
Thermal energy from light fuel oil	MJ	0.070
Thermal energy from LPG	MJ	0.014
Thermal energy from natural gas	MJ	3.3

Table 3-5: Gate to Gate data for the waste water treatment process for the production of Nickel Sulphate

Inputs	Unit	Quantity
Chlorine	kg	7.2E-06
Flocculant	kg	7.0E-04
Sulphuric acid	kg	1.8E-04
Lime	kg	3.8E-04
Sodium hydroxide	kg	1.2E-03
Iron chloride	kg	1.2E-04
Water (waste water; untreated)	kg	51
Hydrochloric acid	kg	6.9E-08
Aluminium sulphate	kg	4.9E-05
Hydrogen peroxide	kg	1.2E-04
Outputs	**Unit**	**Quantity**
Water kept in loop (internally recycled)	kg	2.6
Antimony to water	kg	8.1E-06
Arsenic to water	kg	9.0E-06
Cadmium to water	kg	3.9E-07
Chromium to water	kg	1.2E-06
Chromium (+III) to water	kg	3.3E-04
Chromium (+VI) to water	kg	5.2E-06
Cobalt to water	kg	6.2E-06
Copper to water	kg	2.5E-06
Iron to water	kg	1.3E-03
Lead to water	kg	4.7E-06
Mercury to water	kg	1.4E-07
Nickel to water	kg	2.9E-05
Selenium to water	kg	2.8E-05
Silver to water	kg	6.6E-09
Titanium to water	kg	6.6E-07
Zinc to water	kg	1.7E-06
Ammonia to water	kg	5.5E-05
Fluoride to water	kg	2.7E-04
Magnesium to water	kg	6.7E-03
Nitrate to water	kg	5.1E-04
Sodium sulphate to water	kg	0.14
Sulphate to water	kg	0.19
Sulphuric acid to water	kg	0.010
Processed water to river	kg	16
Solids (suspended) to water	kg	6.8E-04
Biological oxygen demand (BOD) to sea water	kg	4.8E-05
Chemical oxygen demand (COD) to sea water	kg	2.8E-04
Total organic bound carbon (TOC) to sea water	kg	4.1E-06
Arsenic to sea water	kg	1.3E-07
Cadmium to sea water	kg	7.8E-07

Chromium to sea water	kg	2.3E-06
Cobalt to sea water	kg	1.1E-06
Copper to sea water	kg	4.6E-07
Lead to sea water	kg	1.2E-07
Manganese to sea water	kg	6.5E-07
Mercury to sea water	kg	1.5E-09
Nitrate to sea water	kg	2.6E-04
Phosphorus to sea water	kg	1.1E-08
Sulphate to sea water	kg	0.091
Processed water to sea	kg	19
Processed water to lake	kg	13
Biological oxygen demand (BOD) to water	kg	5.1E-05
Chemical oxygen demand (COD) to water	kg	2.9E-04
Total organic bound carbon (TOC) to water	kg	2.0E-06
Manganese to water	kg	2.4E-03

The water balance shown in Table 3-6 mainly represents the water balance around the mine and beneficiation. There were only few instances where a primary extraction site could not provide water separately hence the water boundary is drawn around the mine to primary extraction site as shown in Figure 3-1. Water balances was always included in for “wet” processes, namely the hydrometallurgical process and refining processes since here water forms part of the overall mass balance (and forms part of product). Therefore, water as an input and output from the primary extraction processes and refining processes are added separately in Figure 3-1, and should be considered in addition to the data presented in Table 3-6.

Water balances remain to be challenging and it can be seen that water output is less than water input. Not shown on the output side is that water is entrained in tailings from the beneficiation processes, as well as tailings from the HPAL process which could account for water missing on the output.

Table 3-6: Water balance for the production of Nickel Sulphate

Inputs	Unit	Quantity
Ground water	kg	30
Lake water	kg	10
Rain water	kg	7.2
River water	kg	21
Process water	kg	50
Outputs	**Unit**	**Quantity**
Water (waste water; untreated)	kg	44
Water vapour	kg	8.5
Processed water to groundwater	kg	0.56
Processed water to lake	kg	42

3.2. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". As the complete inventory comprises hundreds of flows, the data presented only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results. These results are placed in Annex A.

4. LCIA Results

This chapter contains the results for the impact categories and additional metrics defined in Chapter 2.4. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1. Detailed Results for Nickel Sulphate

The results for the LCIA for the production of 1 kg nickel sulphate ($NiSO_4$) is presented in the sub chapters below.

For ease, the below table provides an explanation of the categories representing the different sources of impacts contributing to the various processes in the production of nickel sulphate and categorised according to the different Scopes defined by the GHG Protocol for corporate accounting [14].

Table 4-1: Description of contributing impact sources according to Scope 1, 2 and 3

Auxiliaries	The production of all upstream auxiliary raw materials such as chemicals	Scope 3
Raw materials	Typically, main metal-containing raw materials sourced from third parties such as other concentrates (not within the scope of participating member companies)	Scope 3
Sulphur	The upstream production of elemental sulphur	Scope 3
Electricity	Electricity from the national / local grid	Scope 2
Electricity generated on site	Emissions associated with electricity generated on site	Scope 1
Direct activities	Combustion emissions associated with fuels, reductants and other process emissions (air and water emissions). Combustion associated with electricity is not included here.	Scope 1
Fuels and reductants	The upstream production of fuels and reductants	Scope 3
Lubricants	The upstream production of lubricants	Scope 3
Explosives	The upstream production of explosives	Scope 3
Waste Water Treatment	Generally municipal waste water treatment. Emissions associated with onsite water treatment are included under direct activities	Scope 3
Water	The upstream production of tap water	Scope 3
Waste	Treatment of all wastes (landfill, incineration)	Scope 3
Transport	Includes the fuel for transport (the production thereof) and combustion of associated fuels	Scope 3
Credit	Impact associated with the credit of by-product assuming the conventional production route of respective by-product	Scope 3

4.1.1. Global Warming Potential

Results are presented for the GWP showing the contribution of the various processes in the production of nickel sulphate as well as the CO2-equivalent split into Scopes as defined in the GHG Protocol [14].

Scope 1: “Direct GHG emissions occur from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment”.

Scope 2: “Scope 2 accounts for GHG emissions from the generation of purchased electricity consumed by the company. Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where electricity is generated”.

Scope 3: “Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services”.

Results for 1 kg of nickel sulphate and Class 1 nickel are not directly comparable, since they are different products. It should also be noted that **results for nickel sulphate are presented as 1 kg of nickel sulphate**, defined as the functional units, and does not refer to nickel contained in nickel sulphate**.**

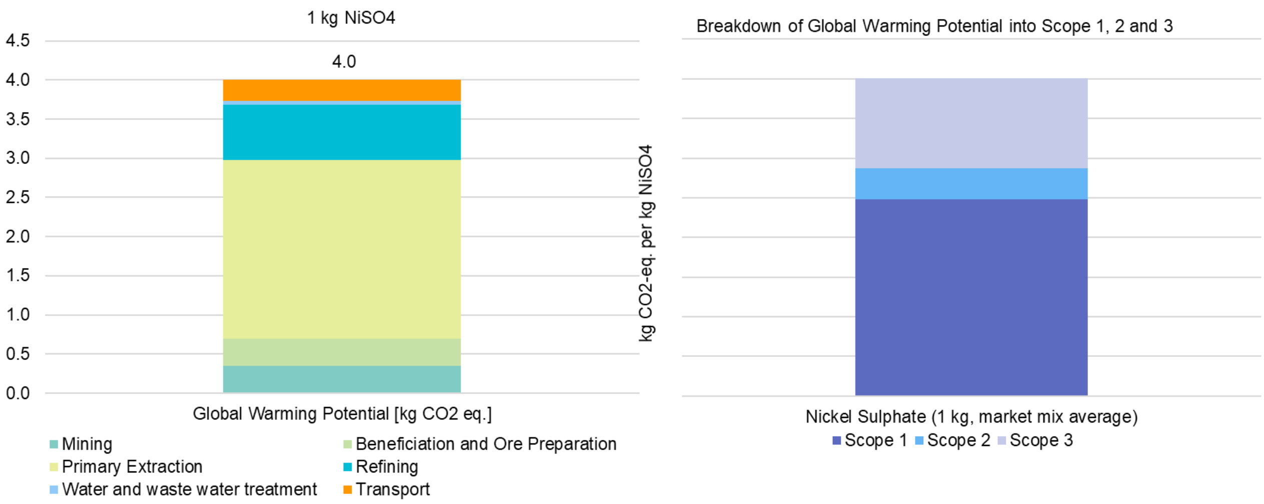

Figure 4-1: GWP for Nickel Sulphate

Figure 4-1 shows that the primary extraction and refining processes contribute 57% and 18% respectively to the GWP for the production of nickel sulphate, while mining and beneficiation makes up 17%. Scope 1 emissions make up 62% of the GWP. Of scope 1 emissions, 53% is a result of electricity generated on site, and the balance fuel combustion and process emissions. Scope 2 emissions makes up 10% of the GWP and is electricity generated from the grid. Scope 3 emissions contributes 28% to the GWP and 61% are due to raw materials and the upstream production of auxiliary materials (mainly chemicals), while 24% is due to transport. Overall CO_2 emissions make up 94% of the GWP, while CH4 makes up about 5% of the GWP.

Although the performance of nickel sulphate and Class 1 nickel cannot be compared directly, since they are different products, it can be observed that the result for GWP (and some other impact categories shown later below) are higher than that for Class 1 nickel when considering the nickel content in nickel sulphate. Whilst nickel sulphate may share a similar upstream production route as

Class 1 nickel leading in the end that the product is derived by means of an allocation, this is not the case for all producers contributing towards nickel sulphate production. There is a greater variation in the ore / raw material and their nickel content than the composition of the producers that make up the Class 1 nickel.

As can be seen in Figure 4-2 emissions attributed to direct activities and electricity generated on site are the major contributions to each process.

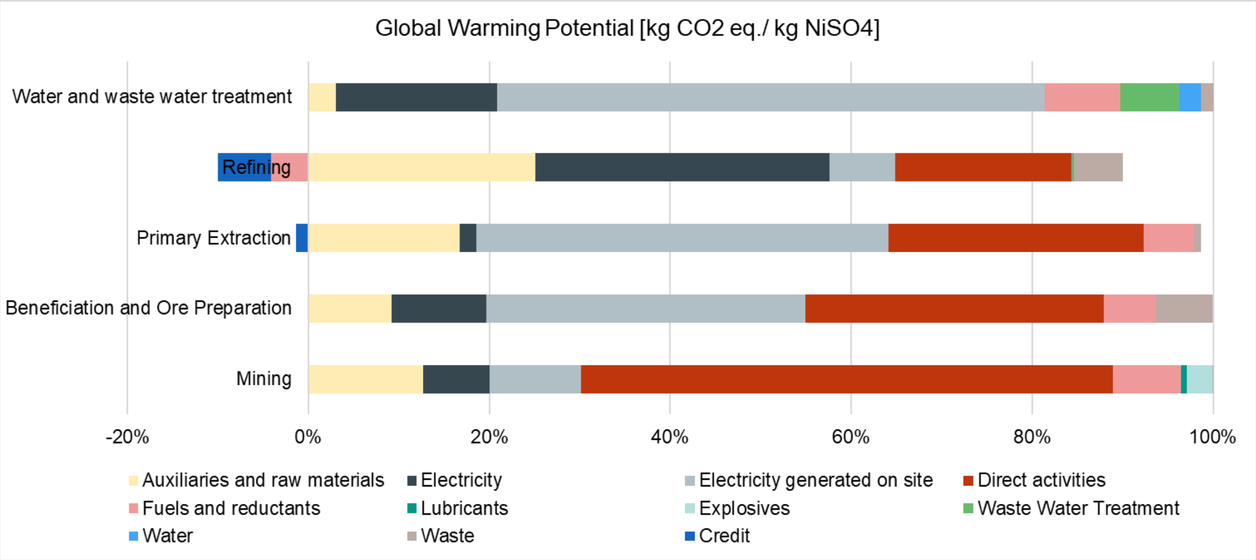

Figure 4-2: Detailed analysis of the GWP for Nickel Sulphate

4.1.2. Primary Energy Demand

The primary extraction and refining processes are also the major contributors to the PED. For nickel sulphate, about 90.4% of the PED is attributed to non-renewable energy resources (fossil fuels and uranium), while 9.6% are renewable. About 45% and 24% of the non-renewable energy sources is from crude oil and natural gas respectively. Figure 4-3 shows the contribution of the different production stages to the PED of nickel sulphate.

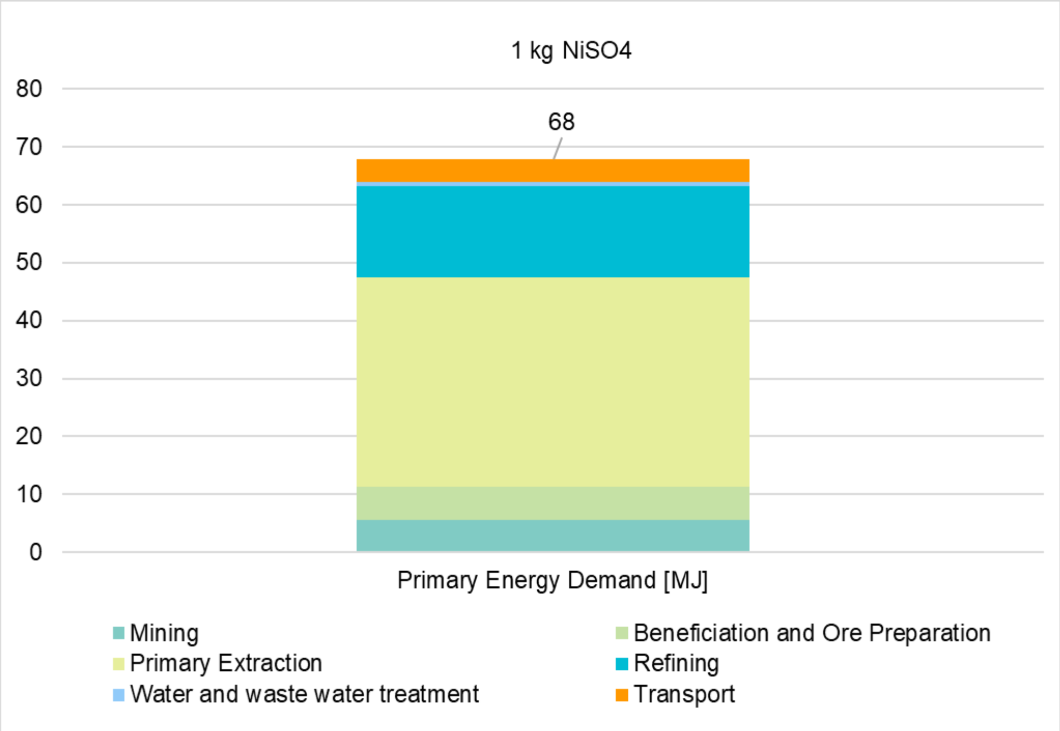

Figure 4-3: PED for Nickel Sulphate

Since the volume of nickel sulphate produced in the study is a mix from the pyrometallurgical processing of sulphidic ore and hydrometallurgical processing of laterite ore, the sulphur required for the hydrometallurgical route is a significant contribution of the PED in the primary extraction process, contributing around 44% to the PED of the primary extraction process. Auxiliary and raw materials in total contributes 47% to the primary extraction processes. Fuels and reductants associated with the pyrometallurgical processing are also significant contributors. In the refining stage, credits are provided for non-metal salts produced as by products and also excess electricity generated and used in other processes outside the system boundary.

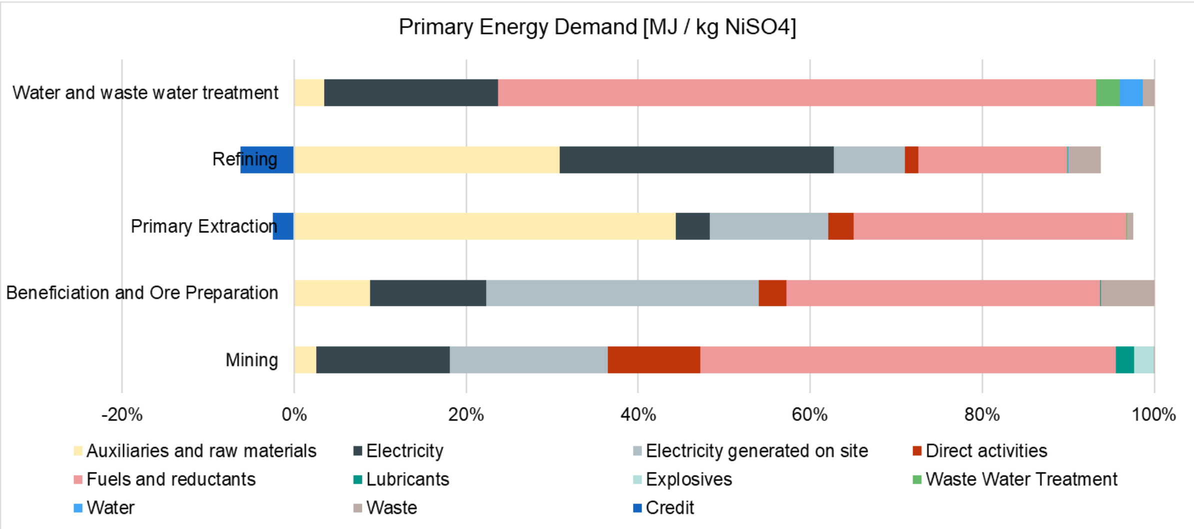

Figure 4-4: Detailed analysis of the PED for Nickel Sulphate

4.1.3. Acidification Potential

The primary extraction process contributes 90% to the AP for the production of nickel sulphate as shown in Figure 4-5. Overall, SO_2 emissions contributes 94% to the AP.

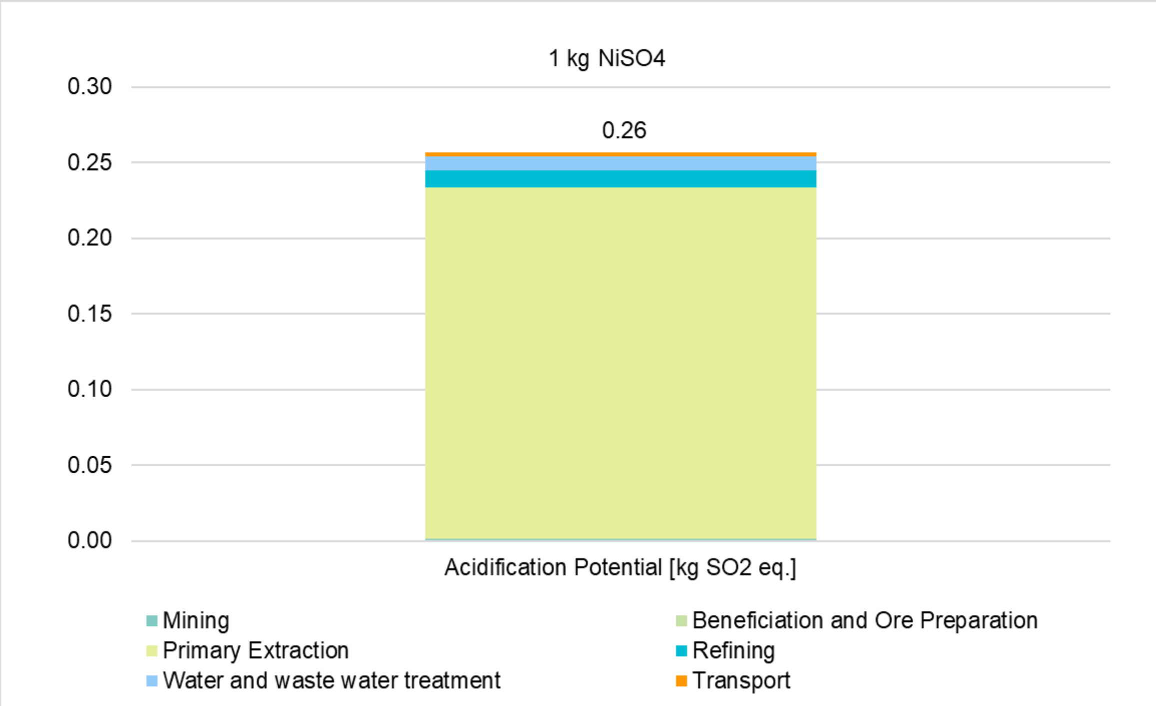

Figure 4-5: AP for Nickel Sulphate

It can be seen in Figure 4-6 that direct process emissions make up almost 100% of the contribution to the primary extraction AP as a result of the pyrometallurgical processes associated with the production of the nickel intermediate as raw material for the production of nickel sulphate.

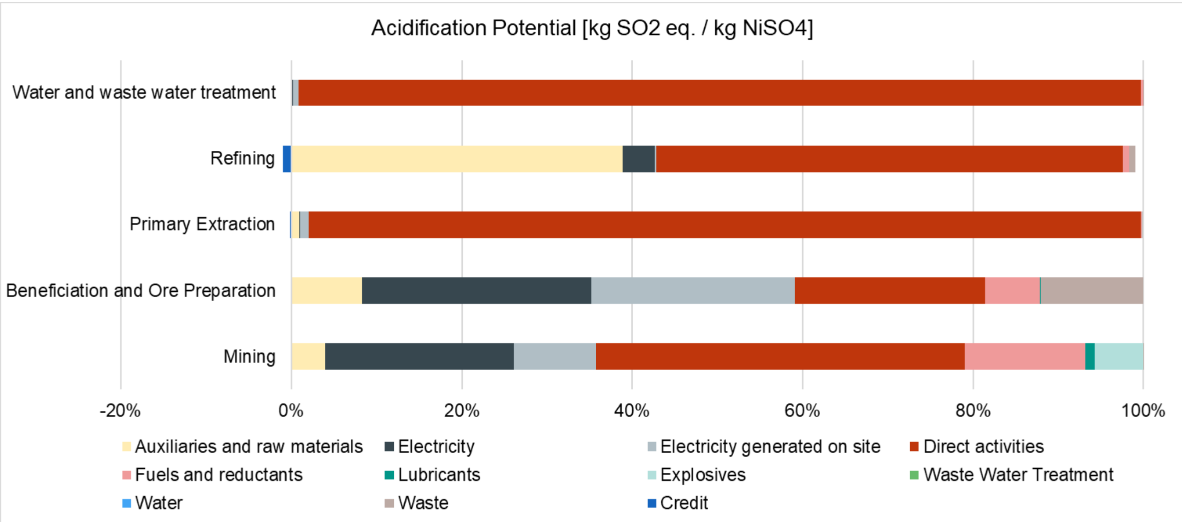

Figure 4-6: Detailed analysis of the AP for Nickel Sulphate

4.1.4. Eutrophication Potential

In the case of the EP for the production of nickel sulphate, transport, associated with the nickel raw materials, contribute a significant 30% as shown in Figure 4-7. In this study, the final refining stages to produce nickel sulphate do not take place at the same site as the production of the nickel raw materials. NOx emissions from the combustion of fuels are the major contributor to the EP as a result of transport. The primary extraction and refining processes together contribute 47%. Overall NOx emissions contribute 70% to the EP of nickel sulphate. Nitrates in emissions to water contributes about 5%, while total emissions to water are 12% of the EP.

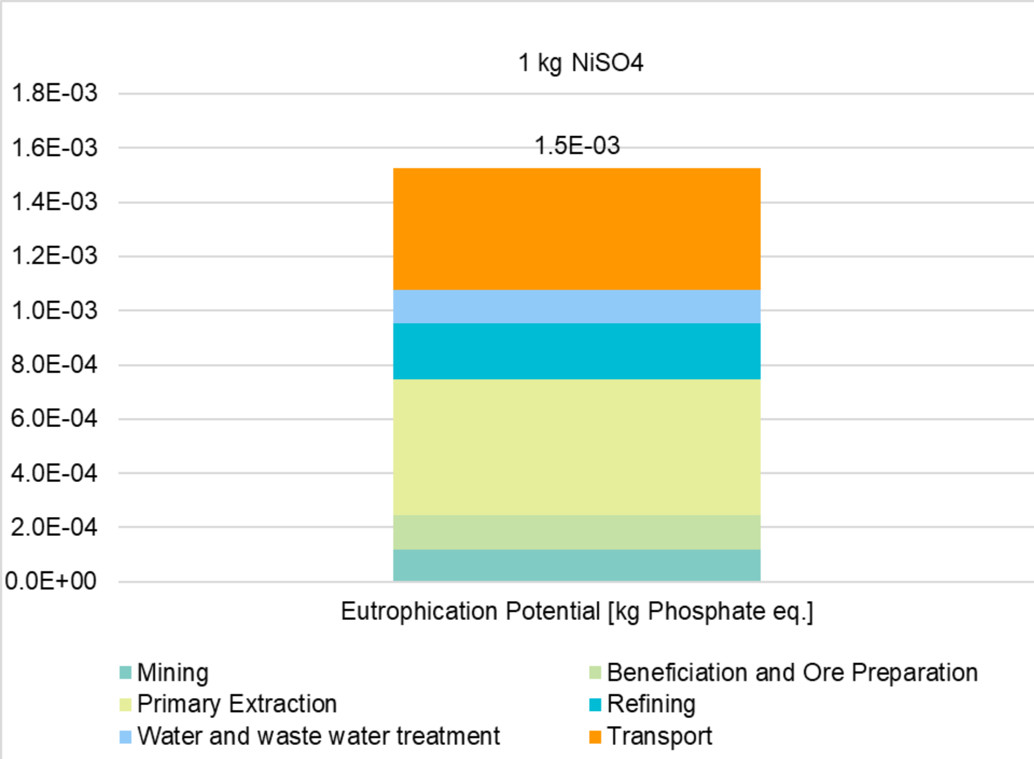

Figure 4-7: EP for Nickel Sulphate

For the primary extraction processes, direct activities including electricity generation on site are the major sources of emissions contributing to the EP. For the refining process, the upstream production of auxiliary materials contributes a significant 42%.

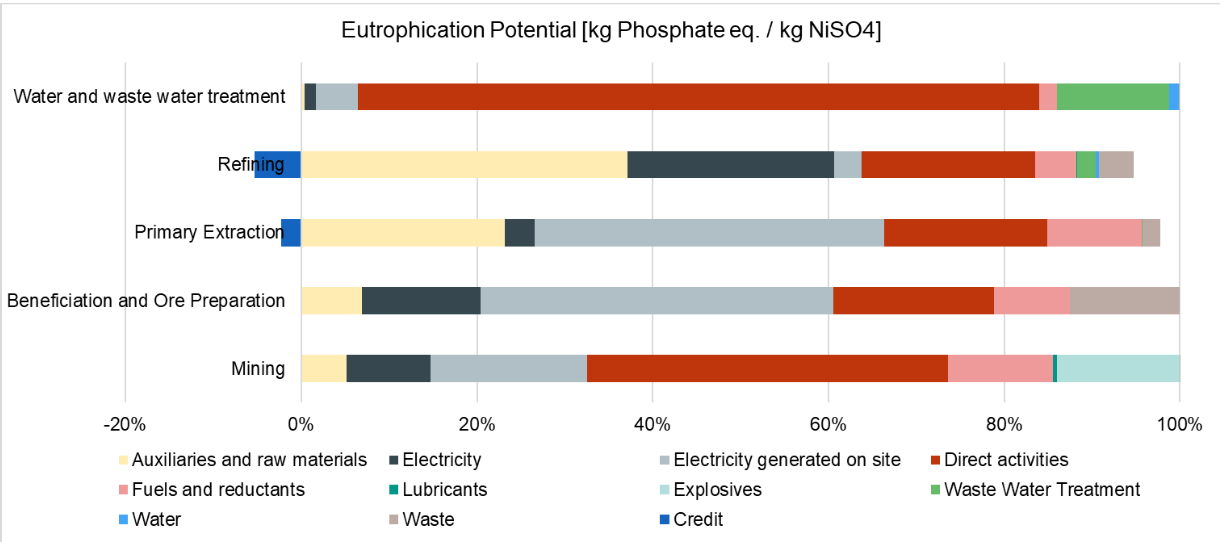

Figure 4-8: Detailed analysis of the EP for Nickel Sulphate

4.1.5. Photochemical Ozone Creation Potential

Figure 4-9 shows that the primary extraction process contributes 95% to the POCP for the production of nickel sulphate. Overall, SO_2 emissions contributes 98% to the POCP for nickel sulphate.

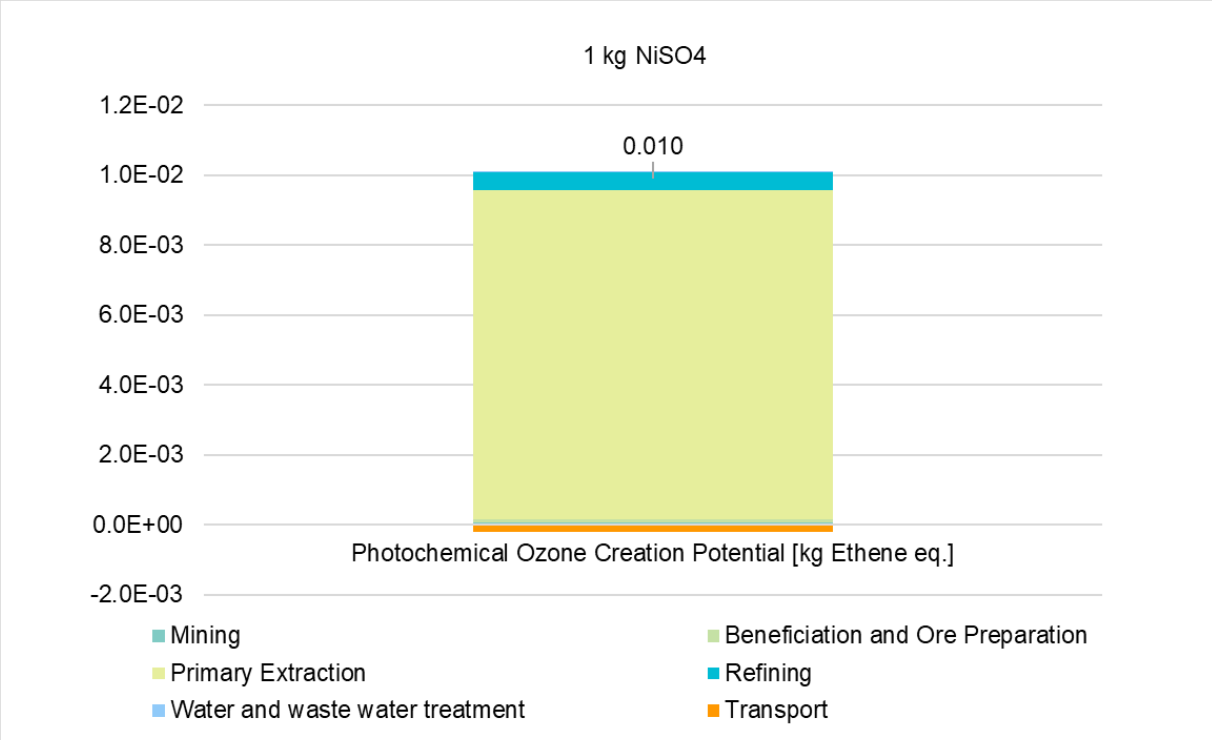

Figure 4-9: POCP for Nickel Sulphate

As can be seen in Figure 4-10, the majority of emissions in the primary extraction process are a result of direct activities with SO_2 emissions from the processing of sulphidic ore being the major contributor to the POCP.

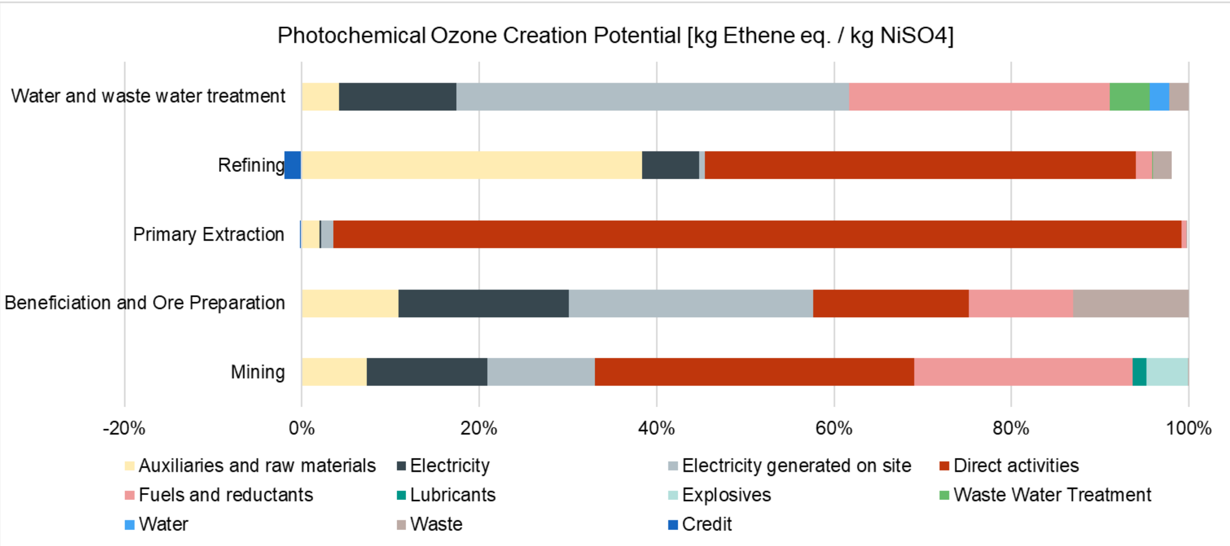

Figure 4-10: Detailed analysis of the POCP for Nickel Sulphate

4.1.6. Blue Water Consumption

Figure 4-11 shows that the refining process accounts for 53% of the blue water consumption for the production of nickel sulphate, while the primary extraction process makes up 33%.

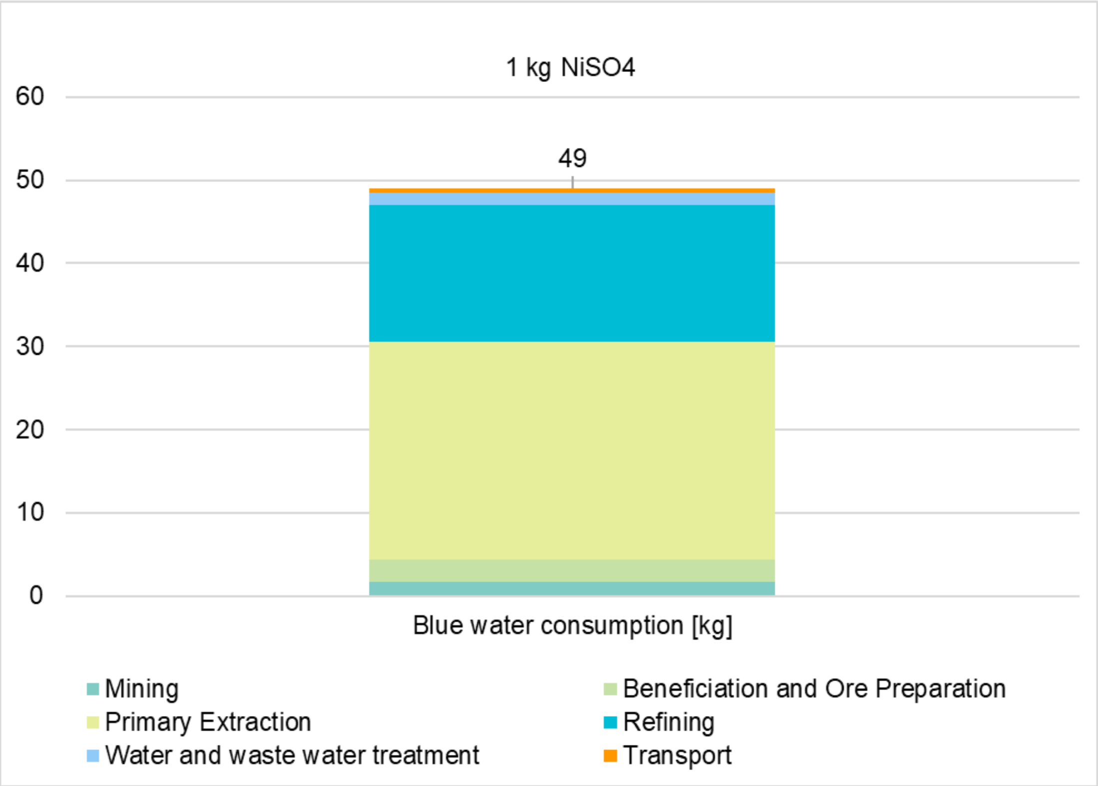

Figure 4-11: BWC for Nickel Sulphate

Figure 4-12 shows that in the primary extraction and refining process, direct consumption of water is the major source of the blue water consumption in refining. Water shown as negative represents water discharged.

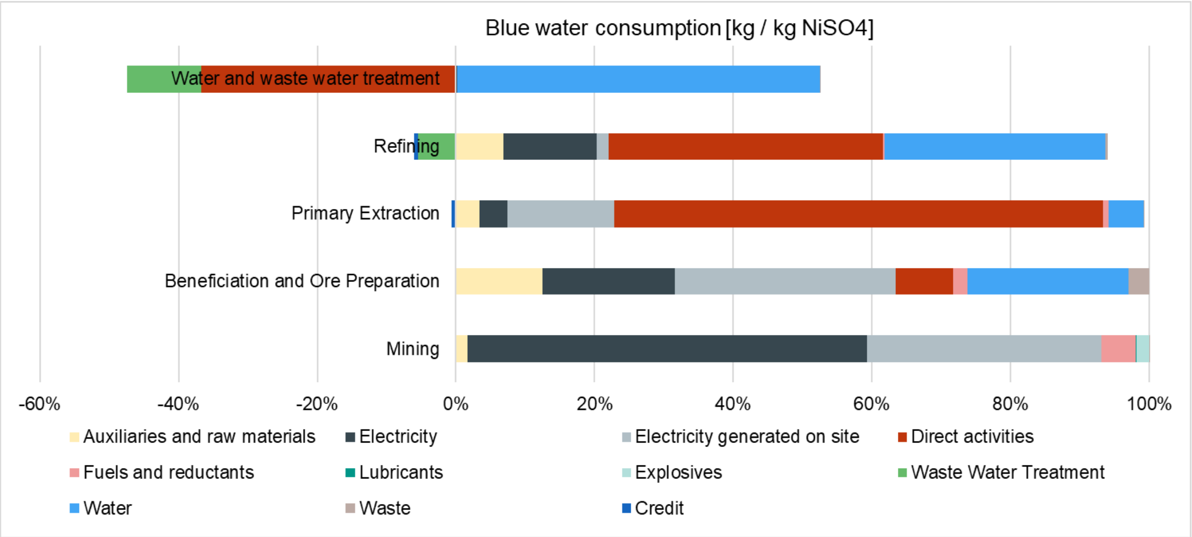

Figure 4-12: Detailed analysis of the BWC for Nickel Sulphate

5. Interpretation

5.1. Assumptions and Limitations

As far as possible, data was defined and collected in accordance with the production processes for each individual company and modelled accordingly. The main assumptions made in this study were to close data gaps, however this was not done in the case of energy as all companies reported this data. The main assumptions relevant to this update are those outlined in the main study[2]. Specific assumptions related to modelling of the market mix are documented in Chapter 3.1.

5.2. Comparison

Nickel Sulphate

The 2017 data represented 15% of world nickel sulphate production from nickel ore, and was based on the production mix (of volumes considered in the study) of three types of feedstock material.

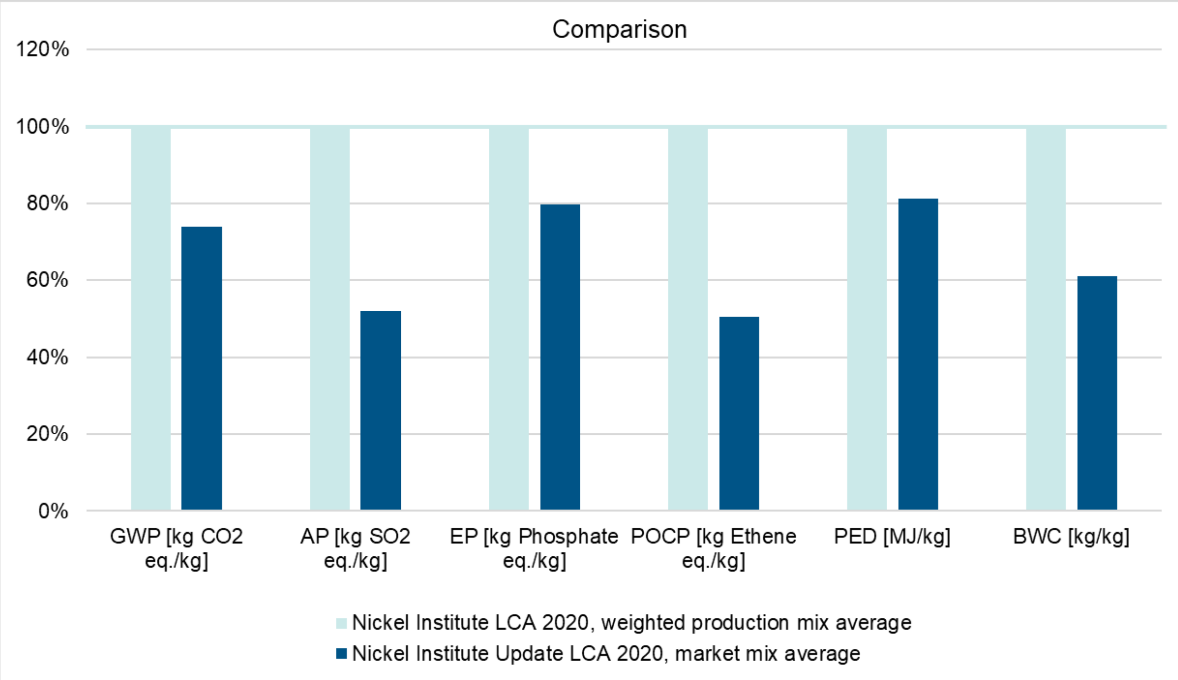

Figure 5-1: Comparison of change in impact categories of market mix result to result in Nickel Institute LCA 2020[2]

5.3. Conclusions and Recommendations

This study has shown that both the primary extraction and refining processes have a significant contribution to the impact categories assessed for the production of nickel sulphate. Figure 5-2 summarises the overall contributors to each impact category. It shows that in the PED, the use of fuels and reductants and sulphur (a major portion of auxiliary and raw materials) are the major sources while this translates to the associated emissions contributing to the impact categories as emissions from direct activities and electricity generated onsite. CO_2, SO_2 and NO_x are the major emissions contributing to impact categories.

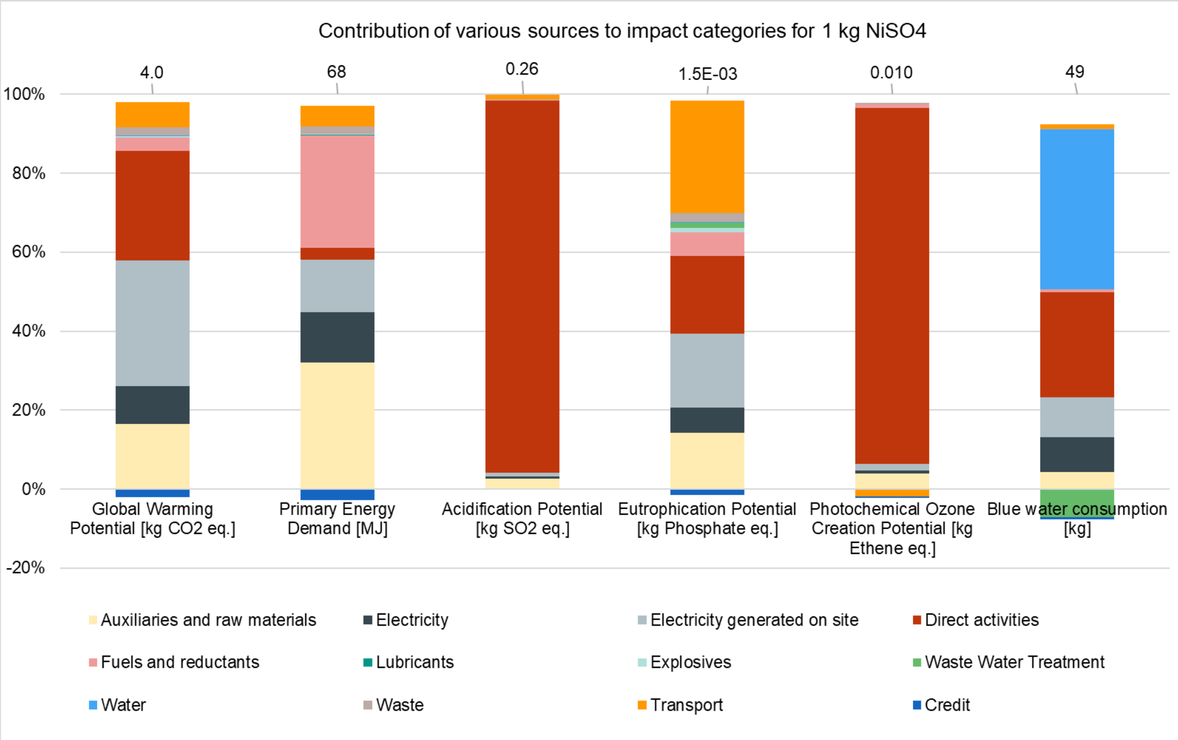

Figure 5-2: Contribution of various sources to impact categories for 1 kg Nickel Sulphate

To ensure a more accurate market mix it is recommended to improve and update the data of $NiSO_4 \cdot 6H_2O$ via the nickel metal route, which is currently based on stoichiometry and literature, with industry data (also considering geographies).

References

[1] ISO, ISO 14040: Environmental management – Life cycle assessment – Principles and framework, Geneva: International Organization for Standardization, 2006.

[2] ISO, ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines, Geneva: International Organization for Standardization, 2006.

[3] JRC, ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance. EUR 24708 EN, 1st ed., Luxembourg: Joint Research Centre, 2010.

[4] Nickel Institute, [Online]. Available: https://www.nickelinstitute.org/about-nickel. [Accessed 28 04 2020].

[5] Nickel Institute, *https://nickelinstitute.org/,* Toronto, Canada: Nickel Institute, 2019.

[6] Nickel Institute, *Nickel Magazine, Volume 2, No.2,* Brussels, November 2001.

[7] Danish Environmental Protection Agency, “Nickel Sulphate - Risk Assessment (Final Version),” Danish Environmental Protection Agency, Copenhagen, March, 2008.

[8] “INSG Nickel Yearbook,” 2019.

[9] IPCC, “Climate Change 2013: The Physical Science Basis,” IPCC, Geneva, Switzerland, 2013.

[10] Guinée, J. B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; de Koning, A.; van Oers, L.; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H. A.; de Bruijn, H.; van Duin, R.; Huijbregts, M., Handbook on life cycle assessment. Operational guide to the ISO standards, Dordrecht: Kluwer, 2002.

[11] Koehler A. Dr., Thylmann D., *Introduction to Water Assessment in GaBi, Version 1.2,* Leinfelden-Echterdingen: thinkstep AG, 2016.

[12] World Bank Group, *Pollution Prevention and Abatement Handbook (Nickel Smelting and Refining),* World Bank Group, 1998.

[13] J. Gabb, Global Mining Research, *HPAL: Upping the Pressure,* Global Mining Research, March, 2018.

[14] World Resources Institute, “Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition),” Washington DC.

[15] L. van Oers, A. de Koning, J. B. Guinée and G. Huppes, Abiotic resource depletion in LCA, The Hague: Ministry of Transport, Public Works and Water Management, 2002.

[16] R. K. Rosenbaum, T. M. Bachmann, L. Swirsky Gold, M. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H. F. Larsen, M. MacLeod, M. Margni, T. E. McKone, J. Payet, M. Schuhmacher, D. van de Meent and M. Z. Hauschild, “USEtox—the UNEP-SETAC toxicity model:

recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment," *Int J Life Cycle Assess, 13(7),* p. 532–546, 2008.

[17] thinkstep, "GaBi LCA Database Documentation," 2014. [Online]. Available: http://database-documentation.gabi-software.com.

[18] BSI, "PAS 2050-1:2012: Assessment of life cycle greenhouse gas emissions from horticultural products," British Standards Institute, London, 2012.

[19] WRI, "GHG Protocol Product Life Cycle Accounting and Reporting Standard," World Resource Institute, Washington D.C., 2011.

[20] IPCC, "2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 - Agriculture, Forestry and Other Land Use," IPCC, Geneva, Switzerland, 2006.

[21] European Union, "Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations," European Union, Brussels, Belgium, 2013.

[22] A. Rabl and J. V. Spadaro, "The RiskPoll Software," August 2004. [Online]. Available: www.arirabl.com.

[23] The Balance, "A List of Base Metals," 13 January 2019. [Online]. Available: https://www.thebalance.com/base-metals-2340104. [Accessed 30 October 2019].

[24] European Commission, "The Montreal Protocol," European Commission, Luxembourg, 2007.

[25] Future Market Insights, [Online]. Available: https://www.futuremarketinsights.com/reports/nickel-sulfate-market. [Accessed 26 06 2018].

[26] Bos U., Horn R., Beck T., Lindner J.P., Fischer M., LANCA® - Characterisation Factors for Life Cycle Impact Assessment, Stuttgart: 978-3-8396-0953-8 Fraunhofer Verlag, 2016.

[27] European Commission, "Product Environmental Footprint Category, Version 6.3," European Commission, May 2018.

[28] PE International, *Harmonization of LCA Methodologies for Metals,* Ottawa, Canada, 2014.

[29] Nassar N.T., Barr R., Browning M., Diao Z., Friedlander E.,Harper E.M., Henly C., Kavlak G., Kwatra S., Jun, C., Warren S., Yang M.Y., Graedel T.E., "Criticality of the Geological Copper Family," *Environmental Science & Technology,* pp. 1071-1078, 2012.

[30] Pfister S., Koehler A., & Hellweg S., "Assessing the Environmental Impacts of Freshwater Consumption in LCA," *Environ. Sci. Technol., 43(11),* p. 4098–4104, 2009.

[31] Goedkoop, M. J.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; Van Zelm, R., "ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation," Ruimte en Milieu, Amersfoort, Netherlands, 2009.

[32] Drielsma, J. A., Russell-Vaccari, A. J., Drnek, T., Brady, T., Weihed, P., Mistry, M., & Perez Simbor, L., "Mineral resources in life cycle impact assessment - Defining the path forward," *International Journal of Life Cycle Assessment,* vol. 21, pp. 85-105, 2016.

[33] Graedel, T.E.; Reck, B.K., "Six Years of Criticality Assessments - What Have We Learned So Far?," *Journal of Industrial Ecology,* 2015.

[34] Lehman. A, Bach. V and Finkbeiner. M, "EU Product Environmental Footprint - Mid Term Review of the Pilot Phase," *Sustainability,* vol. 8, no. Sustainability 2016, p. 92, 2016.

[35] Mila i Canals, L.; Romanya, J.; Cowell, S. J., "Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA)," *Journal of Cleaner Production,* pp. 1426-1440, 2007.

[36] World Resources Institute, *Mine the Gap: Connecting Water Risks and Disclosure in the Mining Sector,* Washington, DC: World Resources Institute, 2010.

[37] United Nations (UN) Life Cycle Initiative, "Global Guidance on Environmental Life Cycle Assessment Indicators, Volume 2," United Nations Environmental Programme (UNEP), 2019.

[38] [Online]. Available: https://www.lppm.com/data/#c=pd&y=2017&t=daily. [Accessed September 2018].

[39] [Online]. Available: http://www.platinum.matthey.com/prices/price-charts. [Accessed September 2018].

[40] [Online]. Available: www.metalary.com. [Accessed September 2018].

[41] [Online]. Available: https://www.onvista.de/rohstoffe. [Accessed September 2018].

[42] [Online]. Available: http://www.finanzen.net. [Accessed September 2018].

[43] [Online]. Available: http://www.quandl.com. [Accessed September 2018].

[44] [Online]. Available: https://www.focus-economics.com/commodities/base-metals/nickel. [Accessed 26 April 2020].

[45] [Online]. Available: https://www.statista.com/statistics/533292/average-price-of-copper/. [Accessed 26 April 2020].

Annex A Cradle to Gate Life Cycle Inventory Results

Table 0-1: Cradle to Gate Life Cycle Inventory for all Nickel Products

Cradle to Gate Inventory		1 kg NiSO4
Analytical measures to fresh water	Biological oxygen demand (BOD)	9.8E-05
	Chemical oxygen demand (COD)	8.4E-04
	Nitrogenous Matter (unspecified. as N)	1.7E-07
	Solids (dissolved)	2.1E-05
	Total dissolved organic bound carbon (TOC)	5.8E-06
	Total organic bound carbon (TOC)	3.4E-05
Analytical measures to sea water	Biological oxygen demand (BOD)	4.6E-05
	Chemical oxygen demand (COD)	2.9E-04
	Nitrogenous Matter (unspecified. as N)	7.0E-09
	Solids (dissolved)	2.4E-10
	Total dissolved organic bound carbon (TOC)	1.9E-14
	Total organic bound carbon (TOC)	4.4E-06
Energy resources	Biomass (MJ)	5.2E-08
	Coalbed methane (in MJ)	6.9E-03
	Crude oil (in MJ)	6.5E-01
	Hard coal (in MJ)	4.9E-01
	Lignite (in MJ)	3.6E-02
	Natural gas (in MJ)	2.9E-01
	Oil sand (10% bitumen) (in MJ)	5.1E-02
	Oil sand (100% bitumen) (in MJ)	4.3E-03
	Peat (in MJ)	5.4E-03
	Pit Methane (in MJ)	4.9E-03
	Shale gas (in MJ)	1.0E-02
	Tight gas (in MJ)	1.8E-02
	Uranium natural (in MJ)	9.9E-06
Heavy metals to air	Antimony	1.6E-08
	Arsenic	2.5E-06
	Arsenic (+V)	5.7E-08
	Cadmium	7.1E-07
	Chromium	4.2E-07
	Chromium (+III)	2.0E-08
	Cobalt	3.7E-06
	Copper	1.0E-04
	Iron	7.2E-07
	Lead	2.0E-05
	Manganese	1.6E-06
	Mercury	2.1E-07

	Molybdenum	1.5E-08
	Nickel	8.6E-05
	Palladium	4.3E-18
	Platinum	4.9E-18
	Rhodium	4.3E-18
	Selenium	1.2E-07
	Silver	4.4E-09
	Tin	6.1E-08
	Titanium	5.9E-10
	Vanadium	1.0E-06
	Zinc	5.4E-06
Heavy metals to fresh water	Antimony	5.6E-09
	Arsenic	5.7E-08
	Arsenic (+V)	2.2E-06
	Cadmium	1.4E-06
	Chromium	4.5E-06
	Chromium (+III)	3.8E-04
	Chromium (+VI)	6.1E-06
	Cobalt	6.8E-06
	Copper	1.3E-06
	Iron	1.8E-03
	Lead	1.0E-06
	Manganese	2.8E-03
	Mercury	1.0E-08
	Molybdenum	3.4E-07
	Nickel	3.3E-05
	Selenium	6.7E-08
	Silver	4.4E-09
	Tin	2.4E-12
	Titanium	5.5E-08
	Vanadium	7.3E-08
	Zinc	2.3E-06
Heavy metals to sea water	Arsenic	1.2E-07
	Arsenic (+V)	3.9E-07
	Cadmium	9.0E-07
	Chromium	2.8E-06
	Chromium (+III)	5.2E-18
	Cobalt	1.1E-06
	Copper	5.7E-07
	Iron	-7.5E-11
	Lead	2.3E-07
	Manganese	6.1E-07
	Mercury	2.4E-09
	Molybdenum	4.7E-18
	Nickel	5.5E-06
	Selenium	1.7E-09
	Silver	1.3E-17
	Tin	1.6E-17
	Titanium	1.7E-18

	Vanadium	7.5E-15
	Zinc	4.0E-09
Inorganic emissions to air	Ammonia	5.6E-05
	Ammonium	-1.4E-06
	Ammonium nitrate	1.0E-18
	Carbon dioxide	3.8E+00
	Carbon dioxide (biotic)	1.6E-01
	Carbon monoxide	3.1E-03
	Chlorine	3.5E-06
	Fluoride	3.8E-07
	Fluorine	5.7E-10
	Hydrogen	1.9E-04
	Hydrogen chloride	3.6E-05
	Hydrogen fluoride	3.1E-06
	Hydrogen sulphide	2.5E-05
	Nitrogen dioxide	1.4E-04
	Nitrogen monoxide	8.4E-04
	Nitrogen oxides	8.2E-03
	Nitrous oxide (laughing gas)	6.5E-05
	Sulphur dioxide	2.0E-01
	Sulphuric acid	1.5E-03
	Water (evapotranspiration)	7.3E+00
	Water vapour	2.2E+01
Inorganic emissions to fresh water	Ammonia	5.4E-05
	Ammonium (total N)	5.6E-13
	Ammonium / ammonia	5.6E-05
	Calcium	4.6E-03
	Carbonate	1.2E-03
	Chloride	1.1E-01
	Chlorine	1.6E-05
	Chlorine (dissolved)	9.7E-06
	Fluoride	8.2E-05
	Fluorine	4.4E-09
	Hydrogen chloride	4.1E-08
	Hydrogen fluoride (hydrofluoric acid)	1.3E-07
	Hydrogen peroxide	5.1E-07
	Hydroxide	6.4E-10
	Nitrate	4.2E-04
	Nitrite	6.2E-09
	Nitrogen organic bound	5.1E-05
	Nitrogen oxides	1.7E-12
	Phosphate	9.8E-06
	Phosphorus	3.1E-06
	Potassium	2.2E-05
	Sodium	2.4E-03
	Sodium hypochlorite	1.2E-05
	Sodium sulphate	1.2E-05
	Sulfate	2.0E-01
	Sulphide	2.2E-04

	Sulphuric acid	1.1E-02
Inorganic emissions to sea water	Ammonia	2.4E-05
	Ammonium / ammonia	1.6E-09
	Carbonate	2.1E-04
	Chloride	1.7E-02
	Cyanide	8.6E-11
	Fluoride	2.4E-08
	Nitrate	2.5E-04
	Nitrite	7.1E-09
	Nitrogen	8.4E-11
	Nitrogen (as total N)	7.6E-14
	Nitrogen organic bound	2.1E-16
	Nitrogen oxides	8.1E-12
	Phosphate	-9.1E-12
	Phosphorus	1.0E-08
	Potassium	1.4E-10
	Sodium	7.7E-06
	Strontium	8.0E-09
	Sulphate	8.6E-02
	Sulphide	3.9E-05
	Sulphur	4.9E-10
Organic emissions to air (group VOC)	Hydrocarbons (unspecified)	2.0E-04
	Methane	7.5E-03
	Methane (biotic)	1.3E-04
	NMVOC (unspecified)	5.6E-04
	Propane	2.5E-04
	VOC (unspecified)	6.8E-09
Other emissions to fresh water	Collected rainwater to river	2.6E+00
	Cooling water to river	5.9E+01
	Processed water to groundwater	6.7E-01
	Processed water to lake	3.3E+01
	Processed water to river	2.6E+01
	Turbined water to river	1.3E+04
Other emissions to sea water	Cooling water to sea	6.2E+00
	Processed water to sea	1.5E+01
Particles to air	Dust (> PM10)	3.4E-04
	Dust (PM10)	1.6E-03
	Dust (PM2.5 - PM10)	1.4E-03
	Dust (PM2.5)	3.1E-04
	Metals (unspecified)	5.1E-10
	Silicon dioxide (silica)	4.2E-10
	Dust (unspecified)	1.0E-04
Particles to fresh water	Soil loss by erosion into water	4.2E-03
	Solids (suspended)	6.3E-03
Particles to sea water	Solids (suspended)	7.0E-04

Stockpile goods	Hazardous waste (deposited)	1.2E-07
	Overburden (deposited)	4.2E+01
	Slag (deposited)	4.2E-11
	Spoil (deposited)	1.3E-01
	Tailings (deposited)	1.5E+01
	Waste (deposited)	2.6E+00
	Ore Stockpile (deposited)	1.1E-01

Annex B ADP Results

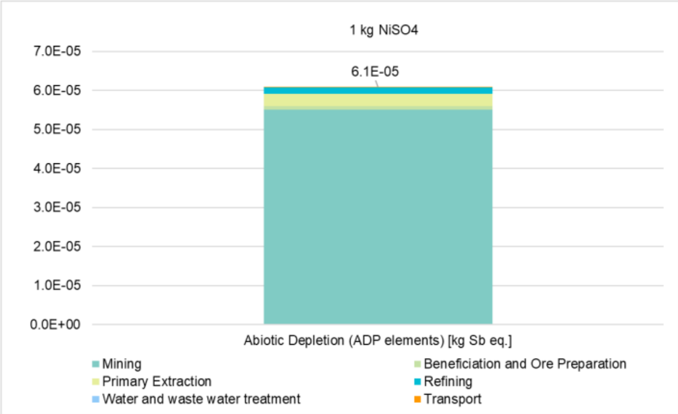

Figure A 1: ADP for Nickel Sulphate

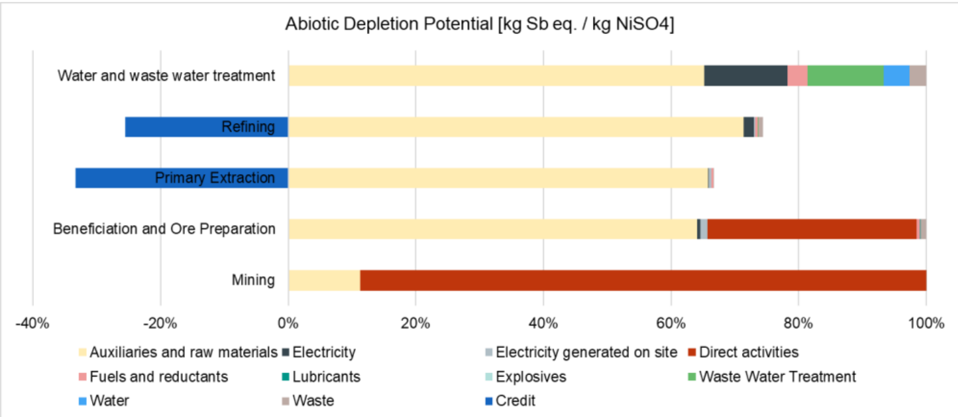

Figure A 2: Detailed analysis of the GWP for Nickel Sulphate

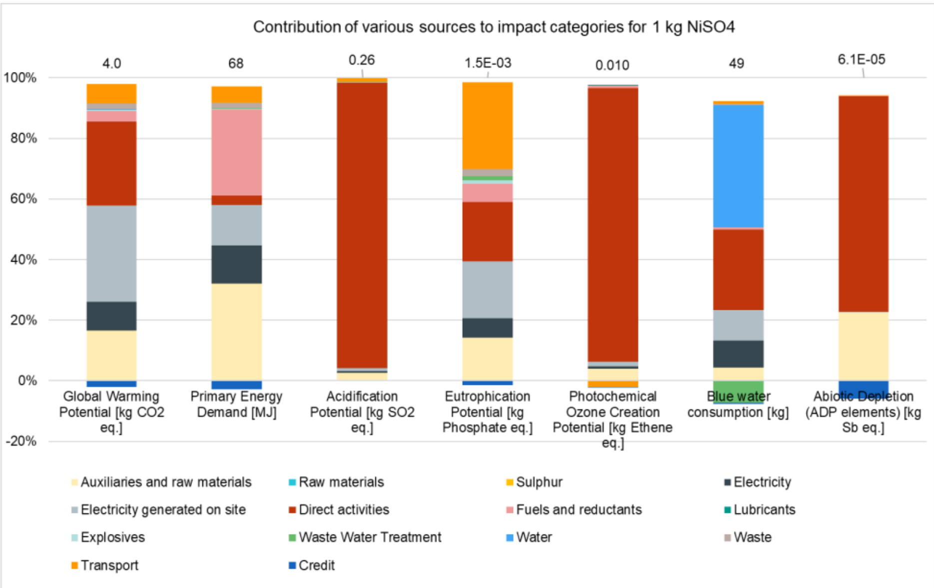

Figure A 3: Contribution of various sources to impact categories, incl. ADP