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The Metals Company – Life Cycle Assessment for TMC’s NORI-D polymetallic nodule project and comparison to key land-based routes for producing nickel, cobalt and copper

Executive Summary

The Metals Company (TMC) has commissioned Benchmark Minerals Intelligence (Benchmark) to model the environmental performance of producing critical minerals from polymetallic nodules found on the seafloor of the Clarion-Clipperton Zone (CCZ), in the Pacific Ocean.

This is a three-part study:
- Part 1: full Life Cycle Assessment (LCA) on TMC processes.
- Part 2: comparison of Part 1 to land-based routes.
- Part 3: waste stream analysis (note that this part has not been third party verified).

This attributional LCA is third party verified and ISO compliant under ISO standards 14040 & 14044. This executive summary provides an overview of the LCA: methodology, key results, and recommendations. It also provides an overview of the TMC's developing process and technology.

Full LCA: Goal and Scope

The goal is to 1) inform The Metals Company (henceforth TMC) and their stakeholders of the potential environmental impacts of producing manganese silicate, Ni/Cu/Co matte, nickel sulphate, cobalt sulphate and copper cathode material from polymetallic nodules (PMN) found in NORI-D, and to 2) compare it to the dominant terrestrial mining routes.

This system is a 'cradle-to-gate' analysis: the 'cradle' starts at raw material extraction and ending with the 'gate' - finished product, before packaging is added, with a system expansion approach to multifunctionality of the system.

Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA)

Metallurgical demand was adopted when applicable. When this was not available, mass and economic allocation were applied. LCI uses primary data from TCM's estimated yearly production and secondary data from Ecoinvent (version 3.8). The midpoint and endpoint categories from ReCiPe 2016 methodology were calculated and calibrated in SimaPro (version 9.4.0.2).

Developing process and technology

Once collected, deep-sea polymetallic nodules are on tidewater and can be transported by ship to an onshore processing site. The study analysed Texas, out of three potential locations: Texas, India and Malaysia, where pyrometallurgical steps can be taken to generate Nickel, Copper and Cobalt (Ni/Cu/Co) matte and Manganese silicate slag. The matte can be further processed via a hydrometallurgical process to obtain refined metals in sulphate form.

Executive Summary

Results

The combustion, production and distribution of bituminous coal were the biggest drivers behind most impact category results for all five of TMC's NORI-D project's products, as shown through the input contribution analysis. The combustion of bituminous coal alone contributed to 63-65% of the Global Warming Potential (GWP) of all products, therefore direct emissions are the major source of GHG emission, making the pyrometallurgical stage the most environmentally impactful stage.

Following ISO, allocation is avoided whenever possible through the identification of sub-processes. The sensitivity analysis shows that the results can be interpreted differently if other allocation methodologies were to be applied. Sensitivity analysis indicates that the results are sensitive to economic allocation and environmental credits, but not to the location of onshore production and variations in metal price.

TMC NORI-D model of all five products resulted in a better environmental performance than analysed traditional land processing routes in the majority of the impact categories, within the mixed allocation methodology applied. For instance, the GWP of TMC NORI-D model are 54-70% lower than the other routes on average. The GWP and water consumption for cobalt sulphate production via the RLE route are the only exceptions. Some explanations for these lower emissions may be due to the absence of blasting and sulphidic tailings in TMC's NORI-D nodule collection processes.

Other reasons for a lower environmental burden include differences in TMC NORI-D's engineered onshore processes which encompass lower energy demand (distributed between co-products), renewable electricity in Texas, high-revenue and high-volume co-products, and high metal recovery rates.

According to the Waste Stream analysis, TMC NORI-D's processes could potentially have less hazardous impact on soil. The mobilised sediment represents the highest volume of material displaced in TMC's NORI-D polymetallic project. However, in comparison to land-based processes, TMC NORI-D would generate less waste overall.

Recommendations

- In order to reduce overall emissions, it is most impactful to focus on finding a replacement for metallurgical coal as a reductant. Alternatives such as biomass pellets should be considered. Natural gas used for heat is also a significant source of GHG emissions.
- Ammonia and sulphuric acid should be sourced from suppliers with less emissions attached to the production or strategically engineered to be used in a more efficient fashion.
- At the time of study, due to time constrains, Benchmark was unable to assess sediment composition. Furthermore, SimaPro is not be equipped to fully capture this impact.
- LCAs only assess environmental impacts covered in the scope and goals of the study. **Therefore, not all environmental issues affected by the product system are covered.**

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Part 1. Life Cycle Assessment of TMC's NORI-D polymetallic nodule project

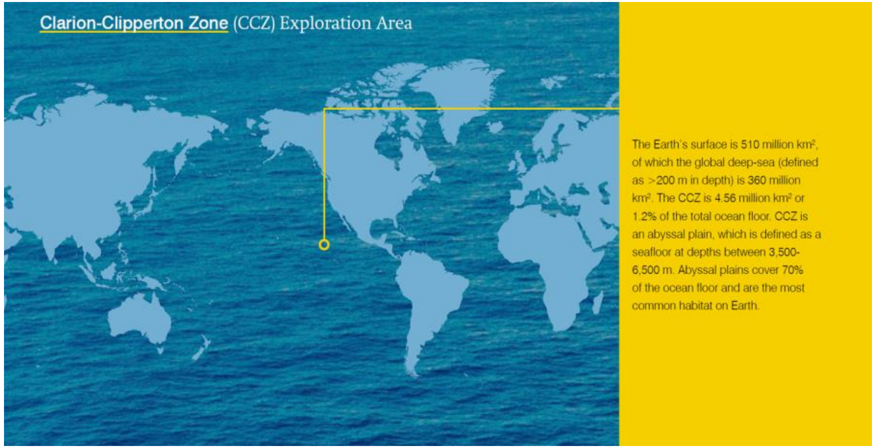
Description of TMC’s process and rationale

The Metals Company (TMC) is developing an unconventional resource, polymetallic nodules to help alleviate the demand deficit of critical minerals and reduce environmental and social problems associated with traditional land-based mining. No commercial collection of polymetallic nodules is currently taking place.

The rationale behind this new resource and reasoning for the efforts in exploring this is due to the demand for critical minerals for the clean energy transition, which is metal intensive.

Electric vehicles require 5 times more minerals than conventional cars[1] and over 300 new mines need to be built to meet this surging demand for electric vehicles and energy storage batteries, even if recycling is considered[2]. Clean energy technologies such as wind and solar energies are also more metal-intensive than fossil fuels.

Polymetallic nodules found at depths of 4 kilometers on the seafloor of the Clarion-Clipperton Zone(CCZ) and contain nickel (Ni), cobalt (Co), copper (Cu) and manganese (Mn) - a potential new source of the metals needed for low carbon technologies.



The Earth’s surface is 510 million km², of which the global deep-sea (defined as >200 m in depth) is 360 million km². The CCZ is 4.56 million km² or 1.2% of the total ocean floor. CCZ is an abyssal plain, which is defined as a seafloor at depths between 3,500-6,500 m. Abyssal plains cover 70% of the ocean floor and are the most common habitat on Earth.

Source: TMC Impact report 2022

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1. IEA, 2021. The Role of Critical Minerals in Clean Energy Transitions, IEA, Paris.

2. Benchmark Mineral Intelligence, 2022. “More Than 300 New Mines Required To Meet Battery Demand By 2035”, link.

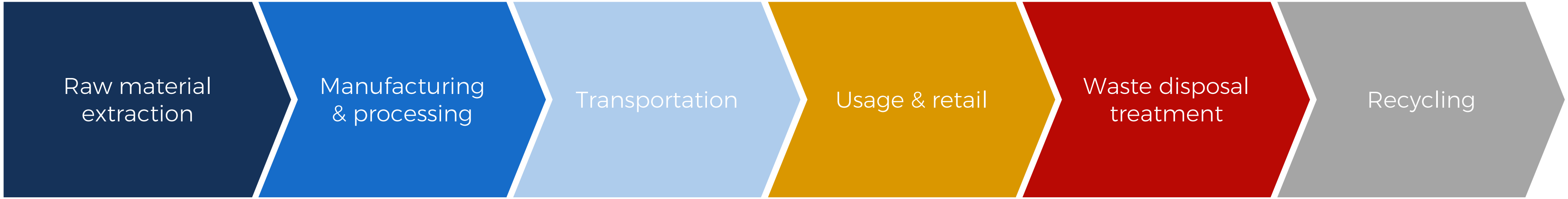
Why a Life Cycle Assessment?

Life Cycle Assessment (LCA) is a tool that offers a method of quantifying and understanding the environmental impacts associated with a product and process systems, to guide product sustainability. It is essential to keep in mind that a LCA is an indicative measure of environmental impacts only, because a LCA is not a complete assessment of all environmental issues relating to a product system.

It is referred to as 'life cycle' because it can take the entire life cycle of a product into consideration - from the raw material stage, referred to as the 'cradle', to the 'end-of life' stage, cited as 'grave'. It is possible to conduct a LCA on a chosen element(s) of the life cycle, through a 'cradle-to-gate' LCA.

The concept of assessing the life cycle for environmental and sustainability purposes has been in practice for over fifty years. LCAs are implemented, and recognised, globally.

LCAs can be used by different stakeholder for different purposes, including benchmarking, tracking, and policy. It is an indicative tool used to give measurable indicators of environmental impacts. There is no widely agreed upon LCA methodology, however ISO 14040 and 14044 provide a framework that LCAs should follow, as well as the most recent draft of the EU Product Environmental Footprint Category Rules (PEFCR) for rechargeable batteries.


Raw material extraction

Manufacturing & processing

Transportation

Usage & retail

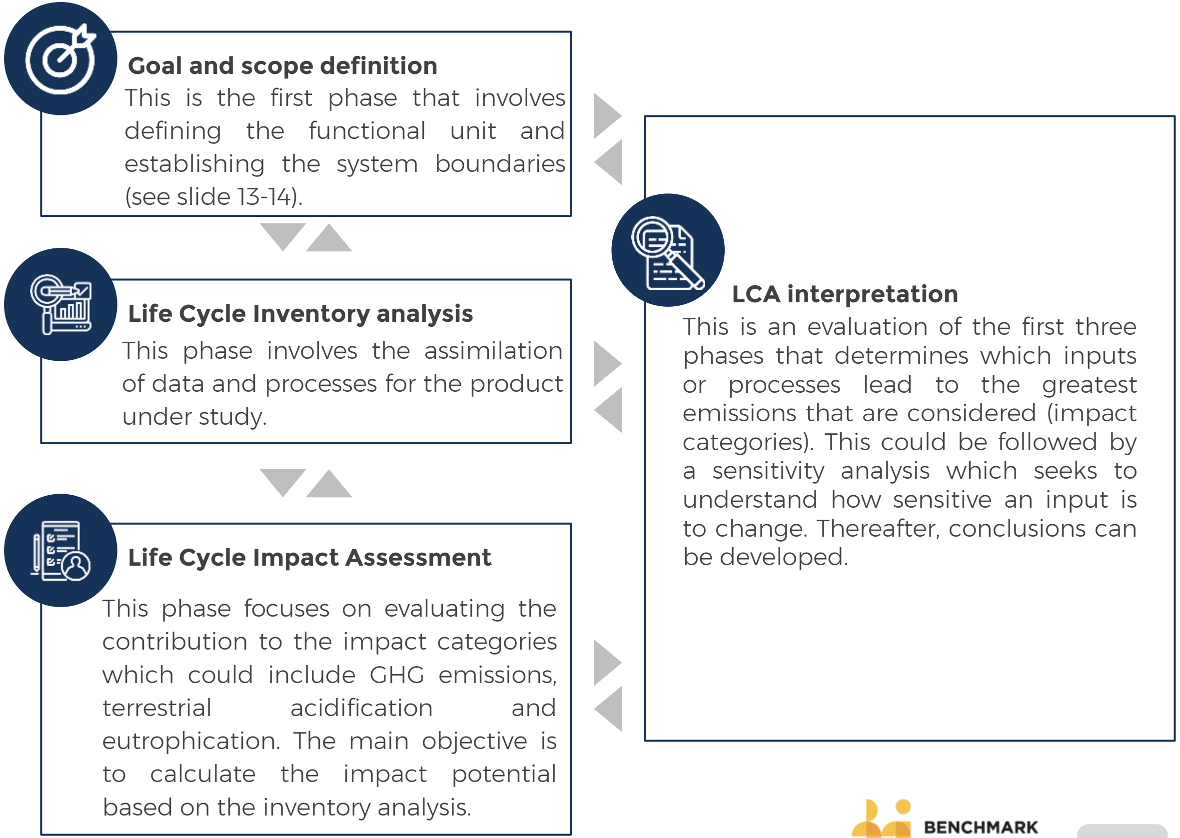
Waste disposal treatment

Recycling

Phases of an ISO compliant LCA

There are four mandatory phases of a LCA (shown here) that must be completed to be compliant with ISO standards 14040 and 14044.

The LCA process is integrated and iterative. This allows for the study goal and scope to be modified, thus reflecting any changes in later stages of the process.



Goal and scope definition

This is the first phase that involves defining the functional unit and establishing the system boundaries (see slide 13-14).

Life Cycle Inventory analysis

This phase involves the assimilation of data and processes for the product under study.

Life Cycle Impact Assessment

This phase focuses on evaluating the contribution to the impact categories which could include GHG emissions, terrestrial acidification and eutrophication. The main objective is to calculate the impact potential based on the inventory analysis.

LCA interpretation

This is an evaluation of the first three phases that determines which inputs or processes lead to the greatest emissions that are considered (impact categories). This could be followed by a sensitivity analysis which seeks to understand how sensitive an input is to change. Thereafter, conclusions can be developed.

Overview and contents of methodology

The scope of a LCA methodology informs how the study goal is implemented. This scope is compliant and transparent to ISO standards 14040 & 14044, the study adheres to these guidelines. It should be noted that "LCA is an iterative technique, and as data and information is collected, various aspects of the scope may require modification in order to meet the original goal of the study." [1] The scope should be sufficiently defined to ensure that the breadth, depth, and detail of the study are compatible and sufficient to address the stated goal. This section will be structured to include the following:

- LCA study goal
- The product system
- The functional units
- The system boundary
- Allocation procedures
- Impact categories and impact assessment method choices
- Data quality requirements (Appendix 1, slide 124)
- Assumptions and limitations

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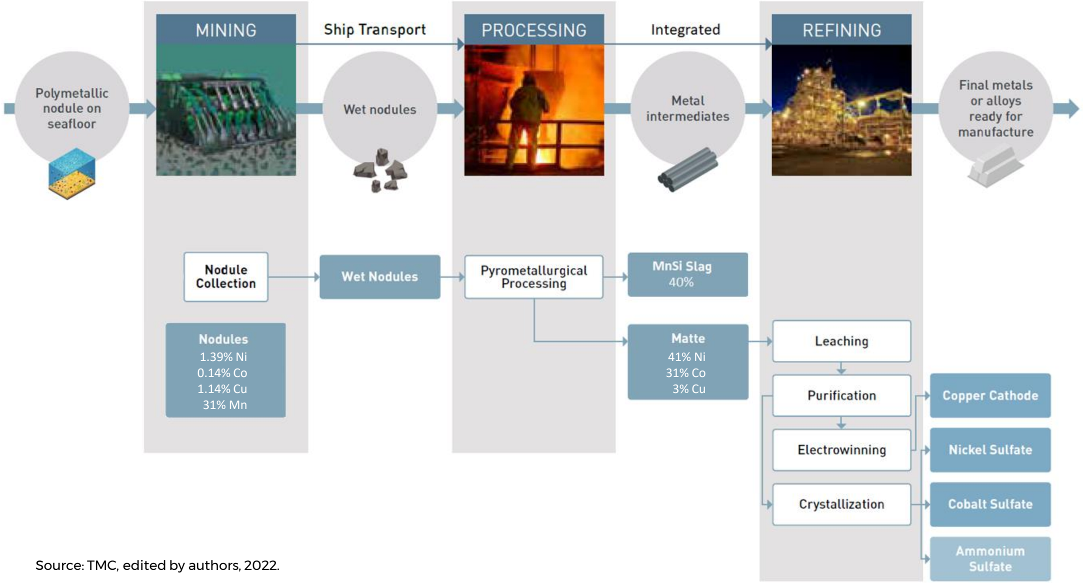
[1] *International Standard ISO 14040, 2006. Environmental Management—Life Cycle Assessment—Principle and Framework.*

LCA study goal

- The objective of this study is to inform The Metals Company (TMC) (the client) and its stakeholders of the potential environmental impacts of their production process (TMC NORI-D project), whilst emphasising any benefits from TMC's operations and opportunities to reduce emissions.
- The inventory focuses on 16 years of steady state production from NORI-D (12.47 mtpa of wet nodules equal to 9.47 mtpa of dry nodules). The onshore flowsheet to process the nodules to final marketed products was developed by TMC with conceptual engineering by Hatch. A mass and energy balance model employing standard metallurgical engineering software (Metsim) to replicate the flowsheet and material flows within was created. The basis for the model was commercial data for the analogous existing metallurgical operations, TMC testwork and piloting data and literature data. The stream flow information from the model was employed to represent a TMC nodule operation at a scale of 6.4 Mtpa (wet basis, 4.88 mtpa dry basis) in this LCA.
- The results from this analysis are compared to Benchmark's identified dominant routes for producing the same metals from commonly used production pathways using conventional land ores from terrestrial mines. Production of these metals from land ores vs. TMC NORI-D's deep-sea nodules are compared side-by-side by using the most current data for analysis.
- Since this is a comparative study, a third-party reviewer is in place to ensure the independence between TMC and Benchmark and that the models are fairly compared.
- The goal is to make this report accessible to a broader audience. With that in mind, this study provides detailed and clear information on the assumptions, methodology choices and results.
- This system is a 'cradle-to-gate' analysis with the 'cradle' starting at raw material extraction and ending with the 'gate' - the finished product (before packaging is added).
- Please note that methodological choices have been replicated as closely as possible to enable comparison. However, in the majority of the terrestrial mining routes detailed, metallurgical demand is unattainable. The decisions for allocation and limitations are described thoroughly in this document.

The product system

Overview of TMC NORI-D’s polymetallic deep-sea nodules process steps

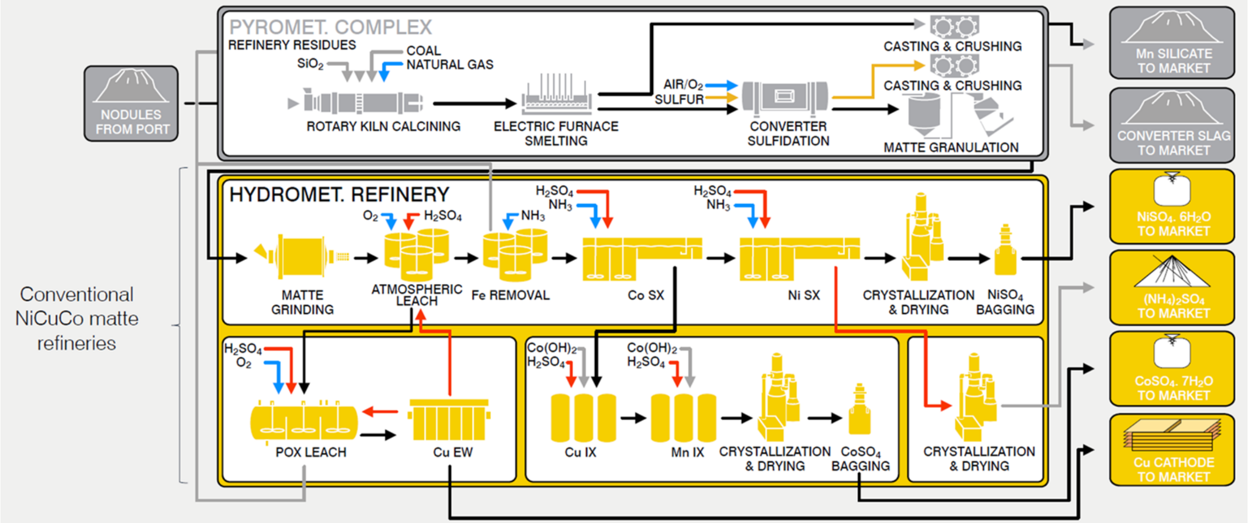


Source: TMC, edited by authors, 2022.

The product system is the data for the Life Cycle Inventory (LCI), which is broken down into unit processes. These unit processes constitute the inputs for the LCIA. The diagram above represents the complete process steps for manufacturing TMC NORI-D’s products - from collecting nodules at the bottom of the ocean floor to refining Ni/Cu/Co matte to produce copper cathode and nickel and cobalt sulphate.

Onshore metallurgical processes in detail

TMC NORI-D’s onshore metallurgical processes



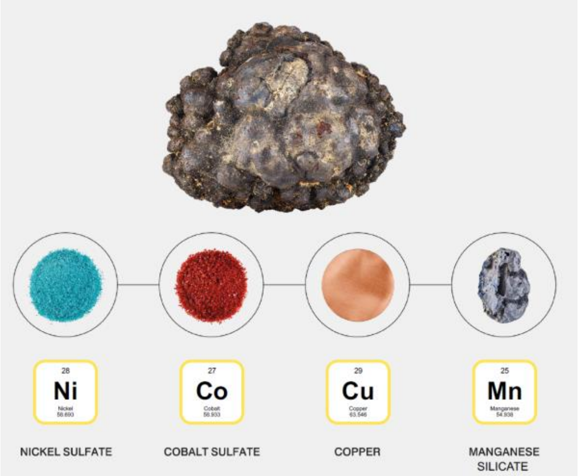
Source: TMC, edited by authors, 2022.

The image above details the onshore processes and its respective inputs and outputs. Manganese silicate (MnSi) leaves the pyrometallurgical stage after being smelted while the alloy continues to sulfidation before granulation. The intermediate product, Ni/Cu/Co matte, goes through further refinement via hydrometallurgical processing where the co-products nickel sulphate, cobalt sulphate, copper cathode are produced, and the by-product ammonium sulphate is obtained.

The functional units

The functional unit for this LCA study defines the quantification of the identified function (performance characteristics) of the product, as defined in ISO 14040.

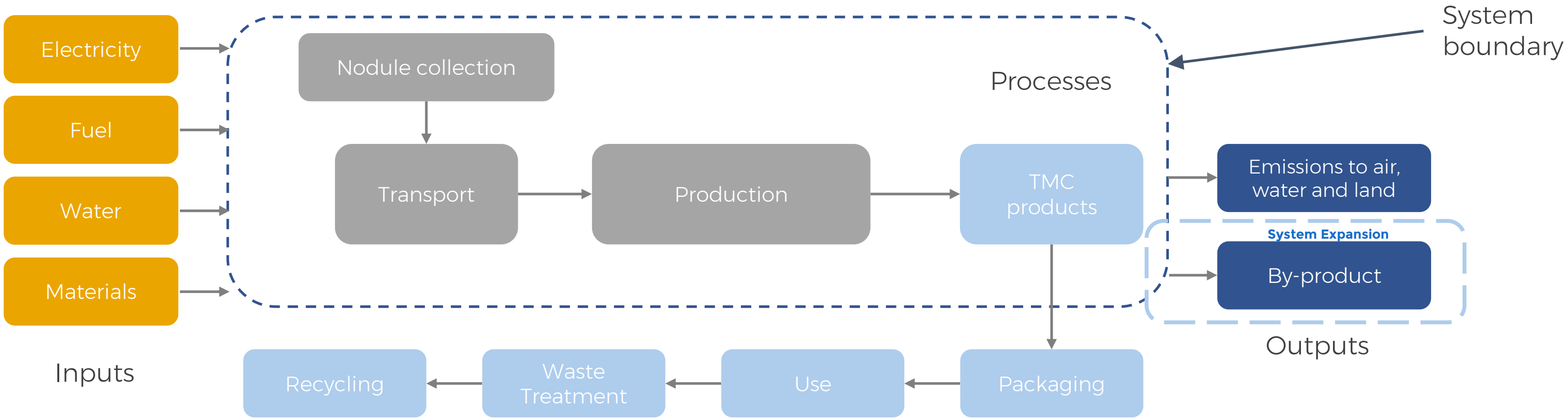
To ensure comparability, the primary purpose of a functional unit is to determine the inputs and outputs that will be included. As the goal of this study is to provide an environmental profile of TMC's products (Nickel, Cobalt, Copper and Manganese Silicate-MnSi), the functional units have been set at:



Source: TMC, 2022

1 kg of Ni/Cu/Co contained in matte
1 kg of MnSi contained in slag
1 kg of Ni contained in Nickel sulphate
1 kg of Co contained in Cobalt sulphate
1 kg of Cu cathode

The system boundary



This diagram locates the system boundary: the dotted line marks the parameter of what is included and excluded from the total product system. The inputs entering the process (e.g. materials) are highlighted in orange, and the outputs in dark blue (e.g. emissions).

TMC requested a 'cradle-to-gate' analysis, therefore the life cycle phases assessed in this LCA include raw material extraction, transportation, manufacturing and processing, as shown in the system boundary (see cut-off criteria on Appendix 1, slide 122).

Locations

Offshore operations happen in the NORI-D area of the Clarion-Clipperton Zone (CCZ). For onshore operations, three locations are investigated in the sensitivity analysis: Texas, India and Malaysia. In the TMC NORI-D model renewable electricity sources were country specific: Texas, wind electricity, is the baseline. The nodules are shipped internationally from Mexico to a port in proximity to a metallurgical facility. No other transportation is considered within the country. This is the most up-to-date data (Ecoinvent version 3.8), and the technology modelled is based on what is currently estimated to be used by TMC operations.

Metallurgical demand - pyrometallurgy

The input **coal** is mainly used to reduce oxides from nodules to achieve, on-specification, Manganese Silicate (MnSi) and Ni/Cu/Co alloy. The reduction of oxides was calculated by TMC through mass balance with basis on testwork and piloting data from analogous commercial operations, and thermodynamic fundamentals such as Gibbs free energy curves. This analysis provided the portion of the carbon in coal that is effectively utilised for direct reduction of the nodule oxides to reach desired MnSi and Ni/Cu/Co alloy. In total, the reduction step uses **80%** of the total coal input. The remaining **20%** of the coal was grouped with natural gas for heat needs and direct energy demands were used to calculate heat requirements of MnSi (**92.5%**) and Ni/Cu/Co alloy (**7.5%**).

According to TMC, the **electricity** consumption is divided between furnace (**88%**) and non-furnace (**12%**) (e.g. conveyor belt). The energy demand at furnace is determined by the same heat requirements described above (**92.5%** - MnSi & **7.5%** - Ni/Cu/Co). The non-furnace consumption is dominated by calcination (**75%**), which is further divided into energy demand and sulfidation (**25%**).

The **sulphur** is consumed only by the alloy Ni/Cu/Co, whereas **69% silica flux** is used by MnSi and the remaining **31%** by Ni/Cu/Co, following the TMC's data.

The **nodule collection** at the mining step, is allocated by mass as the relationship is purely physical to the volume of MnSi (**93%**) and Ni/Co/Cu in matte (**7%**) produced.

The remaining inputs, water and electricity used by operations vehicles, were mass allocated.

All the breakdowns described above are also represented in the life cycle inventory (LCI) (Appendix 1, slides 132-136).

Allocation procedures

Most industrial processes yield more than one product; therefore allocation of environmental impacts should be attributed to these products fairly. This is referred to as the 'allocation procedure'.

According to the ISO 14044 standard, allocation should be avoided when possible. Due to the production of multiple products, the allocation can only be avoided by identifying sub-processes in the pyrometallurgical step and applying knowledge of the specific metallurgical and energetic demands of each of the products in the flowsheet. As a result, allocation was avoided for key inputs such as coal, natural gas, electricity, silica flux and sulphur. For the remaining inputs, such as the wet nodules collected, water and electricity for an onsite fleet, mass allocation was used.

Due to the importance of grade in the products analysed in this LCA, the metal content is considered instead of full mass. For the hydrometallurgical step, economic allocation was applied.

- **Mass allocation** was applied in the pyrometallurgical step where metallurgical demand would not define consumables needs (e.g. conveyor belt). The step involves smelting and the separation of manganese from the other metals, therefore a sensitivity analysis is completed to show the effect of economic allocation.
- **Economic allocation** is applied in the hydrometallurgical step where the metals are refined and separated. Due to the significant price variance between the final products, this procedure was deemed appropriate. Furthermore, there is a harmonisation pledge within the metal sector where academics[1] and industry[2] agree with the methodology. A sensitivity analysis is performed to show the effect of price variation.
- **System expansion** was adopted for the by-product ammonium sulphate and the converter slag, the latter will be used as gravel. Due to the high volume of sulphate production, a sensitivity analysis is also provided.

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[1] *Santero and Hendry, 2016. Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.*
[2] *Nickel Institute, 2022. How to determine GHG emissions from nickel metal Class 1: A guide to calculate nickel's carbon footprint.*

Impact category considerations, classification and characterisation

Considerations

ReCiPe 2016 considers all midpoint impact category indicators (illustrated on diagram).

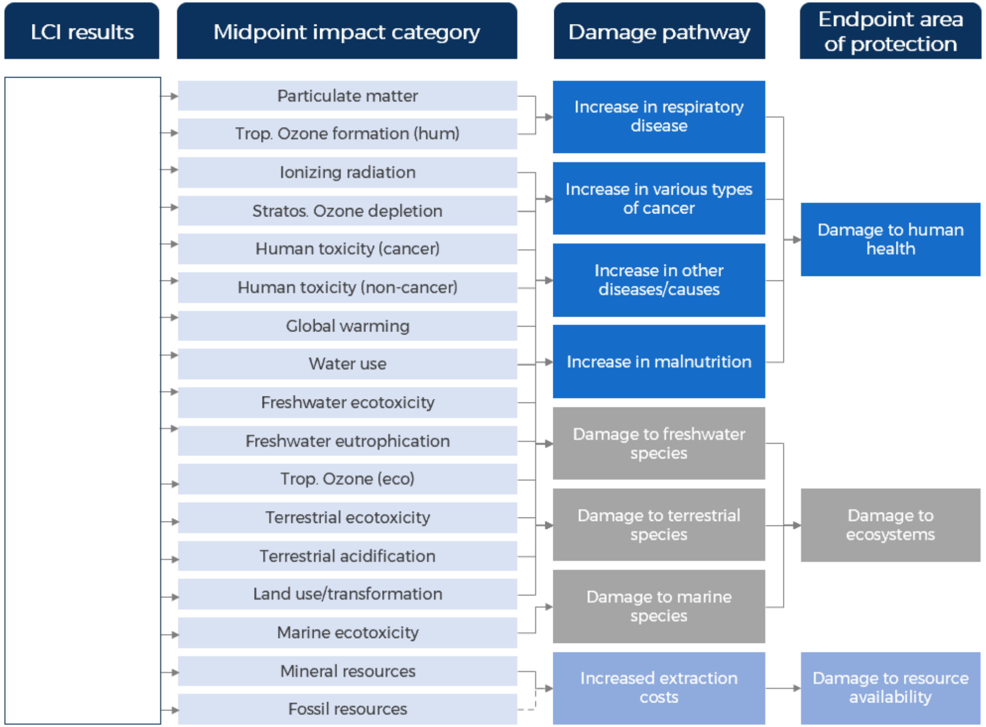
This diagram shows that the midpoint categories link to damage pathways which link to the endpoint indicators. Here shows that endpoints give a high-level impact without indicating a source and give high statistical uncertainty.

Classification of LCI results form the inputs of the midpoint category and are assigned by ReCiPe 2016 methodology.

The **characterisation** of results calculates the impact category based on characterisation factors pre-assigned and developed within ReCiPe 2016.

Following the industry need, seven critical impact categories were selected. This process is explained in the summary of LCIA results.

The client also requested the high-level analysis of endpoint impacts.



SimaPro. 2021. Updated ReCiPe2016 Implemented in SimaPro.

Impact categories and impact assessment method

Midpoint impact categories

The seven impact categories below, all critical environmental impacts of the metal industry[1], are defined during the LCIA phase. The full list of impact categories within ReCiPe 2016 can be found in Appendix 1, slide 146. In addition to these midpoint impact categories, this LCA will also investigate and report on damage categories (endpoint).

Impact Category (ReCiPe 2016)	Details
Global Warming Potential	Emissions included: carbon dioxide, carbon monoxide, methane, nitrous oxide, chlorofluorocarbons and hydrochlorofluorocarbons (**in kg CO_2-equivalent to air**).
Stratospheric Ozone Depletion	Chemicals that cause the depletion of the ozone layer have chlorine or bromine groups in their molecules that interact with ozone (mainly) in the stratosphere. Ultimately they cause human health issues because of the resultant increase in UVB-radiation (**in kg CFC-11-equivalent to air**).
Terrestrial Acidification	Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in the acidity of the soil. Major acidifying emissions include NO_x, NH_3, or SO_2. This can cause extinction of species leading to damage to the terrestrial ecosystem (**in kg SO_2-equivalent to air**).
Freshwater Eutrophication	Occurs due to the discharge of nutrients into soil or into freshwater bodies and hence in the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen (**in kg P-equivalent to freshwater**).
Marine Eutrophication	Occurs due to the discharge of nutrients into marine environments and hence in the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen (**in kg N-equivalent to marine water**).
Particulate Matter Formation	Represents a complex mixture of organic and inorganic substances. PM2.5 can cause human health problems as it can deposit to the upper part of the airways and lungs when inhaled. Secondary PM2.5 aerosols are formed in air from emissions of sulphur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x), among other elements (**in kg PM2.5-equivalent to air**).
Water consumption	Attributed to the availability reduction of freshwater which leads to impacts on human health and ecosystem quality (**in m^3 water consumed**).

1. Santero and Hendry, 2016. Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.

Impact categories and impact assessment method

Endpoint categories: Areas of Protection

The followings categories are the three selected areas of protection in ReCiPe 2016 which demonstrate the environmental impact on or the damage to human health, ecosystems/natural environment and resources. The results of each area of protection are the aggregated results from the midpoint impact categories, hence called endpoint categories, which show the environmental impacts at a higher level.

Areas of Protection (ReCiPe 2016)	Details
Human Health	The years lost or that a person is disabled due to a disease or accident (**in disability adjusted life years, DALY**)[1].
Ecosystems	The respective potentially disappeared fraction of species in terrestrial, freshwater and marine ecosystems are integrated into the local species loss over space and time (**in species year**)[1].
Resources	The extra costs involved for future mineral and fossil resource extraction (**in $**)[1].

The detailed methodology of life cycle impact assessment (LCIA) comprising the methodological choices, data requirements and data quality requirements can be found in Appendix 1.

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1. Huijbregts M, Steinmann Z, Elshout P, Stam G, Verones F, Vieira M et al., 2016. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22(2), pp.38-147.

Assumptions

It is inevitable that LCAs will apply assumptions and have limitations associated with the methodology, however it is essential that these are transparent. This enables interpretation to represent the current product system with the gaps that may exist. The LCA process relies on subjective decisions (e.g. selecting data and models) which are informed, but not specified, by ISO standards. Here, each choice is justified to ensure study robustness.

Assumptions

- Lazaro Cardenas port is used for practical purposes in this LCA. TMC affirms that a port on the west coast of North America (Mexico) will likely be used to consolidate nodules in transshipment vessels.
- Transport vessels from/ to NORI-D and transfer port assume round trip journeys.
- One-way journey is assumed for transshipment from Mexico to the onshore processing destination. It is common practice to have different renters for the container ship as the costs are too high for an empty journey.
- Oxygen production is confirmed to be on-site, by a third party. The proxy for liquid oxygen from Ecoinvent is edited to represent this production. Transportation is excluded and the electricity is changed to renewable sources in accordance with TMC's operations.
- The survey vessels are assumed to be similar to an oceanographic research vessel with the weight based on water displacement of 3,200 tonnes[1].
- The direct emissions from the onshore operation were not fully engineered at the time of this analysis. The pyrometallurgical emissions are known (CO_2, CO and SO_2) and were compared to proxies available in SimaPro. For methodological uniformity in the onshore processes, both stages (pyrometallurgical and hydrometallurgical) have proxies in the model for the coal and natural gas emissions. These proxies are edited to best represent the processes' environment and reactions.
- According to TMC, a precipitator to remove particle matter from the pyrometallurgical step will be in place. Therefore, a conservative estimate of 95% removal efficiency is assumed following standard operations data and literature review[1].
- For coal, the proxy "Heat, district or industrial, other than natural gas {RoW}|heat production, at coal coke industrial furnace 1-10MW" is copied, edited with project specific data and adopted.
- For natural gas, the proxy "Heat, district or industrial, natural gas {RoW}|heat production, natural gas, at industrial furnace >100kW" is copied, edited with project specific data and adopted.
- The closest proxy for mining vessels are tankers for petroleum. The process includes material consumption, end-of life, energy consumption, machinery and emissions from paint and solvents.
- The closest proxy for transport vessels are bulk carriers for dry goods. The process includes material consumption, end-of life, energy consumption, machinery and emissions from paint and solvents.
- The closest proxy for transshipment vessels are container ships. The process includes material consumption, end-of life, energy consumption, machinery and emissions from paint and solvents.
- None of vessels on Ecoinvent sufficiently represents the survey and support vessels. Therefore, long liners made of steel are chosen to account for material consumption, machinery and end-of life. Steel represents 94% of the material consumption.

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[1] *Lee, J.-B. et al. (2011) "Emission rate of particulate matter and its removal efficiency by precipitators in under-fired Charbroiling restaurants," The Scientific World JOURNAL, 11, pp. 1077–1088..*

Limitations

General limitations (ISO 14040)

- The life cycle impact assessment (LCIA) only assesses environmental impacts covered in the scope and goals of the study. Therefore, not all environmental issues affected by the product system are covered[1].
- There is a constraint for the LCIA due to the limited development of characterisation models, uncertainty and sensitivity analysis[1]. For instance, ecological impacts such as deep water habitat/species' behavioural changes cannot be explicitly communicated through the characterisation models.
- In terms of the life cycle inventory (LCI) phase, cut-offs and data gaps are involved in establishing the system boundary[1].
- Uncertainties are present in allocation and aggregation procedures of data[1].
- There are no generally accepted methodologies to associate LCI data with specific potential environmental impacts consistently and accurately[1]. The LCIA results are therefore, estimates of the real-world impact only. Modelling for impact categories is still in development.
- Although the Ecoinvent database used (v 3.8) was released in September 2021, the data contained in the database was not updated to 2021 numbers. For example, the electricity mix statistics are 2014 statistics.

Study limitations (TMC NORI-D model)

- The results might not fully reflect the potential environmental impacts of actual operation due to two main reasons. Firstly, the uncertainty arise from the absence of a set of readily available inventory data since deep sea mining is still a developing industry. The offshore inventory data collected is based on TMC's conservative estimates at commercial scale. However, it it is not the operational data. Similarly, it is uncertain which onshore site will be used for the hydrometallurgical and pyrometallurgical processes. Secondly, the methodological choices e.g. allocation methods and characterisation of results in LCA introduces uncertainties in describing the reality.
- Given the complexity, developing nature of the application, an specific field of knowledge related to plume behaviour, it is believed that SimaPro is not equipped for an in-depth analysis. The sediment plumes impacts are something that TMC is researching, inclusive of ongoing field tests and samples (lead by the company and independent researchers). In this LCA, mobilised sediment is modelled as overburden.
- The coal proxies available in Ecoinvent were too limited to represent TMC's input, so hard coal is a conservative approximation.
- Electricity proxies are also approximation of the technologies that will be in place. The power production and infrastructure (e.g. installation) do not match reality due to limited library options on Ecoinvent.
- Studies have shown that the ocean is a carbon sink and deep waters specifically allow carbon to remain for a longer period of time which is then buried in sediments[2,3]. However, these carbon sinks are outside the scope of this study since SimaPro (v 9.4.0.2) is yet to incorporate ocean carbon in its calculation algorithm.

1. International Standard ISO 14040, 2006. Environmental Management—Life Cycle Assessment—Principle and Framework.
2. Ma C, You K, Ji D, Ma W, Li F., 2015 Primary discussion of a carbon sink in the oceans. J Ocean Univ China, 14(2), pp. 284–292.
3. Mackenzie FT, Lerman A, Andersson AJ, 2004. Past and present of sediment and carbon biogeochemical cycling models. Biogeosciences, 1(1), pp. 11–32.

Model specifications

The base model '**TMC NORI-D**' assumes the region as the site for the onshore operations. The port location determines the choice of renewable electricity sources for onshore operations as a metallurgical plant will be chosen close by. For offshore activities, the marine gas oil consumption is determined by the distance to be travelled by the vessels. The difference between other possible locations is addressed in a sensitivity analysis.

1) Distance from port-to-port: 3,686 nautical miles

2) Electricity production: wind turbine, onshore

The LCI focused on 16 years of steady state production from NORI-D (12.47 Mtpa of wet nodules equal to 9.47 Mtpa of dry nodules). The onshore flowsheet to process the nodules to final marketed products was developed by TMC with conceptual engineering by Hatch. The stream flow information from the model was employed to represent a TMC nodule operation at a scale of 6.4 Mtpa wet basis (4.88 Mtpa dry basis in this LCA.

Several production scenarios are considered:

- 100% production in TMC plant;
- shared production TMC / tolled;
- 100% tolled production.

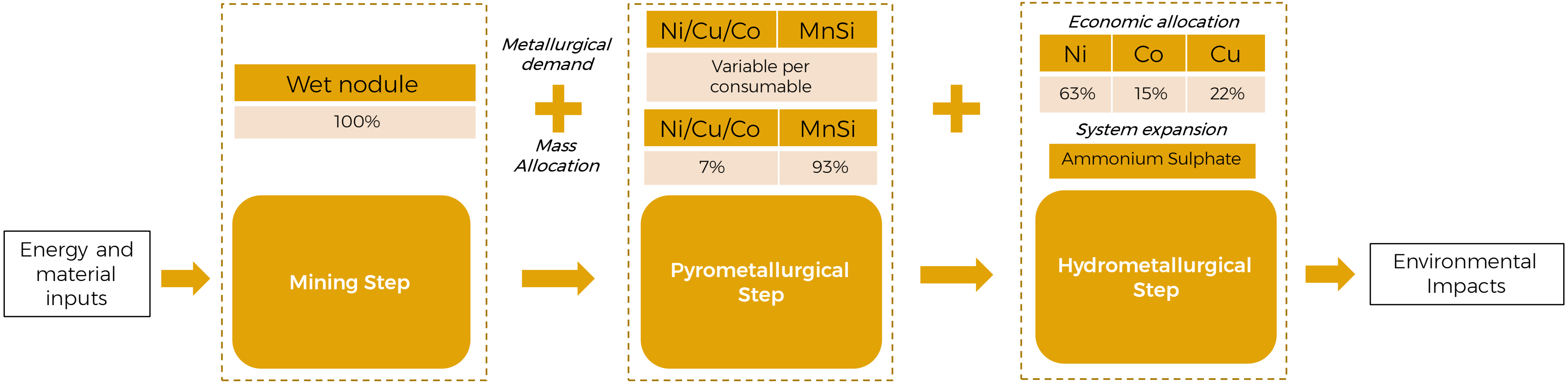
However, **100% production in TMC plant** is adopted in this LCA because TMC's pyrometallurgical and hydrometallurgical flowsheets are essentially the same as existing facilities. Additionally, TMC is committed to choose tolling partners that source 100% of their electricity from renewables.

This model analyses five possible end-products in TMC's production. The company might produce and sell the intermediate matte product and the manganese silicate slag based on downstream user preference of metal format. Alternatively, TMC might further process the intermediate matte to achieve, in the final stage, nickel sulphate, cobalt sulphate and copper cathode. Since each final product might have different stakeholders and different buyers, the results are divided in chapters where each functional unit can be understood as a single product.

The methodology is the same throughout all functional units and each system has the same reference flow.

Allocation of flows and releases

The method of allocation is important because it can cause drastic differences in the environmental impacts. As stated in the scope, there are three allocation procedures, namely mass allocation, economic allocation and system expansion, for this system process that have been given a value which must be highlighted in the LCI. In addition to the scope allocation procedures, the metallurgical demand needs to be included here. Although this has previously been stated, it is an essential stage under ISO 14040 to re-state certain aspects of the scope throughout each phase of the LCA.


Energy and material inputs

Wet nodule
100%

Mining Step

Metallurgical demand

Mass Allocation

Ni/Cu/Co	MnSi
Variable per consumable	

Ni/Cu/Co	MnSi
7%	93%

Pyrometallurgical Step

Economic allocation

Ni	Co	Cu
63%	15%	22%

System expansion

Ammonium Sulphate

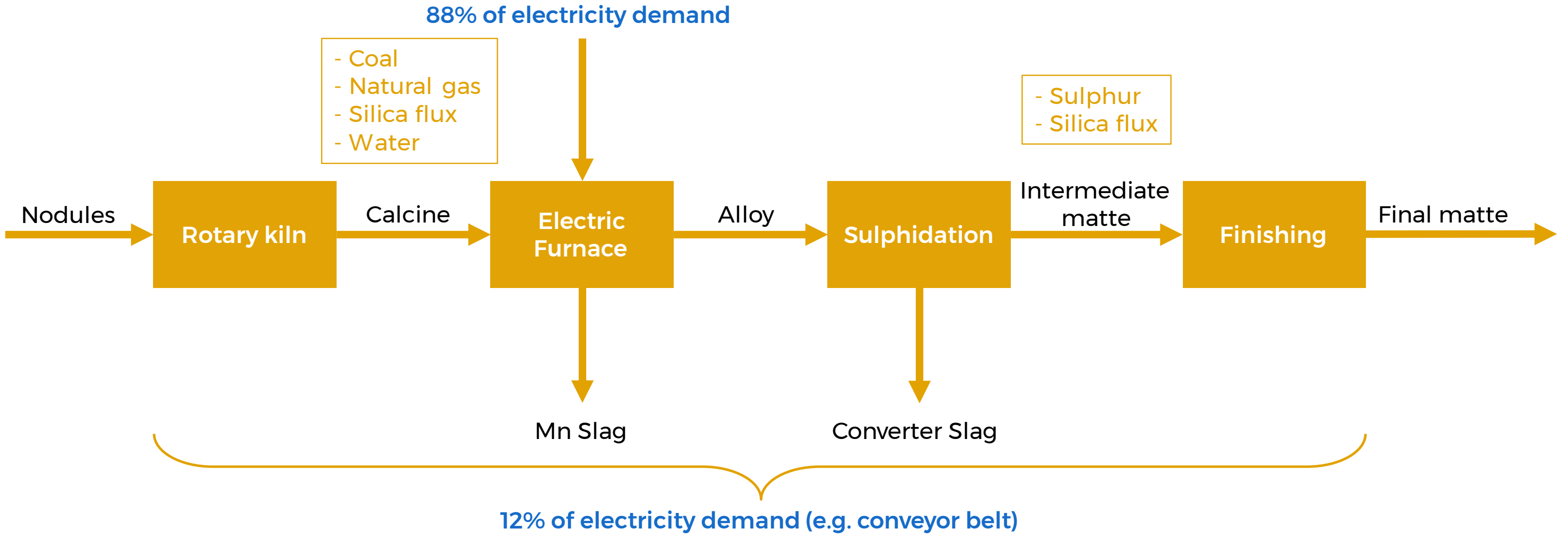
Hydrometallurgical Step

Environmental Impacts

Metallurgical demand - pyrometallurgical

Following ISO 14044, allocation should be avoided whenever possible. Because of that, the pyrometallurgical step is divided into sub-processes. This diagram shows the differences in metallurgical requirements for Manganese Silicate (MnSi) and the alloy (metals). Coal, natural gas and electricity are broken down by energetic need between MnSi and metals. Sulphur and silica flux are used in different stages of the process.

Pyrometallurgical step – sub-processes were identified to avoid allocation when possible



Mass allocation - pyrometallurgical

Allocation is necessary in the **pyrometallurgical step** because more than one product is produced and, for some inputs, metallurgical demand is not applicable. In the LCI tables, Appendix 1 - slides 132-136, the mass allocation percentages applied are in green (wet nodules collected, makeup water, electricity for electric fleet, and steam emissions).

Due to the importance of grade in the products analysed in this LCA, the metal content is considered instead of full volume. Otherwise, impurities would share the responsibility for the production of these metals. In this case, **93%** of the final production is Manganese Silicate (MnSi) and **7%** are other metals (Ni/Cu/Co) within the matte.

The mass of **wet nodules collected** at the mining stage is physically connected to how much is produced, therefore mass allocation is appropriate. Thus, products such as **water and electric fleet** are not directly related to Manganese Silicate (MnSi) or the metals, therefore the allocation rule is applied for consistency.

$$\mathit{Mass\ allocation} = \frac{\mathit{metal\ content\ produced}}{\begin{matrix}\mathit{sum\ of} \\ \mathit{total\ metal\ content\ produced}\end{matrix}}$$

Economic allocation - hydrometallurgical

Allocation is also necessary in the hydrometallurgical step. In the LCI tables, Appendix 1 - slides 137-143, the economic allocation percentages are in blue.

The purpose of this stage is separating the metal contained in the matte. Since each metal yields a different price in the market. economic allocation is appropriate.

The prices of these metals vary from year to year because of the effects of supply and demand. A ten year average is adopted as recommended by the metal industry[1].

Real price	Timeframe	Price per tonne	Source	**Allocation**
Cobalt, real 2021	10 year value (2011-2021) $/t	USD 43497	Benchmark	**14%**
Copper, real 2021	10 year value (2011-2021) $/t	USD 7635	World Bank	**22%**
Nickel, real 2021	10 year value (2011-2021) $/t	USD 16575	World Bank	**64%**

$$Economic\ allocation\ = \frac{metal\ content\ produced*avg\ price\ per\ tonne\ of\ metal}{\begin{array}{c}sum\ of\\ total\ metal\ content\ produced*avg\ price\ per\ of\ metal\end{array}}$$

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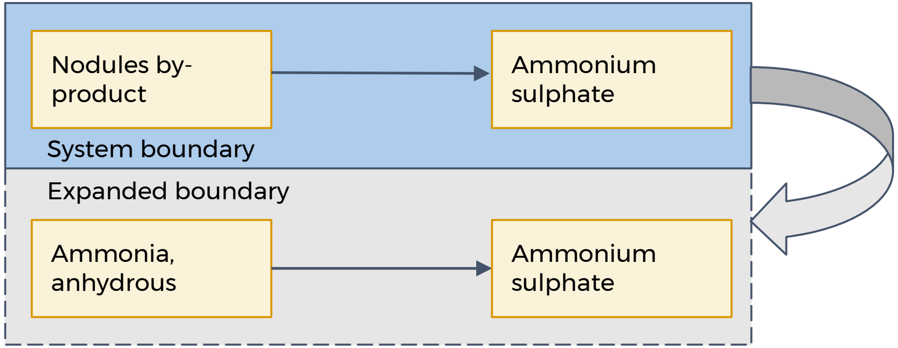
[1] *Santero and Hendry, 2016. Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.*

System expansion allocation

Both pyrometallurgical and hydrometallurgical processes yield by-products. These are unintended products that have none or low economical value to TMC's revenue.

It is suggested as a harmonisation effort by academia and industry[1,2] that such by-products are allocated by system expansion, meaning that the product system is expanded to incorporate the functions of an alternative route. In the route chosen, these products would occur intentionally, and not as a result of another production process. Therefore, a credit is given in accordance with the savings of the emissions avoided, in-theory, by not needing such alternative processing.

The converter slag will be granulated and can be utilised or donated by TMC as construction material such as gravel to pave local roads. Ammonium sulphate will be sold externally. A sensitivity analysis is provided to determine the influence of such methodological choices.



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1. Santero and Hendry, 2016. *Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.*
2. Nickel Institute, 2022. *How to determine GHG emissions from nickel metal Class 1: A guide to calculate nickel's carbon footprint.*

Data collection and calculation, inputs for models

In order to complete the data collection and calculation phase of the LCI, all data collected has been validated by TMC and Benchmark. The data should relate to each unit process within the product system, and the data must relate to the reference flow and functional unit.

Functional unit: the LCI values are based on annual production which are normalised to 1 kilogram of critical metal(s) contained in TMC's product(s) in the SimaPro model.

1. Ni/Cu/Co contained in matte
2. MnSi contained in slag
3. Ni contained in Nickel sulphate
4. Co contained in Cobalt sulphate
5. Cu cathode in their respective systems.

Reference flow: the amount of inputs or products required in a particular system in order to fulfil the functional unit (annual production).

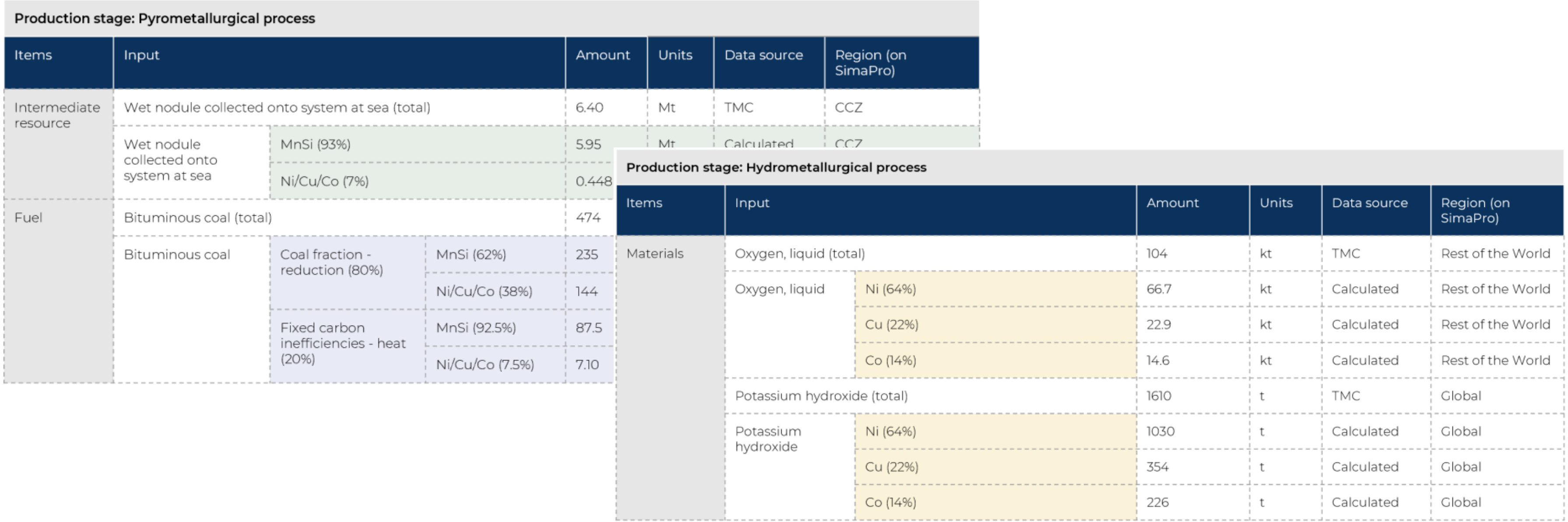
The tables in the Appendix 1 - slides 125-143 display the amount required for each inputs or products, in relation to the processes previously described in the system boundary.

Data quality requirements are found on Appendix 1, slide 124.

Life Cycle Inventory analysis

This is the data collection and calculation phase of a LCA. It has been conducted in consultation between TMC and Benchmark to ensure study goal alignment within the data collection phase, an iterative process. The creation of a life cycle inventory (LCI) data inputs/outputs table is the main objective for this phase. The requirements for these tables are specified within the scope, specifically the functional unit, data requirements, data quality, and the system boundary.

The full LCI detailing the inputs and outputs of offshore and onshore (pyrometallurgical and hydrometallurgical stages) operations can be found in Appendix 1.



Production stage: Pyrometallurgical process

Items	Input			Amount	Units	Data source	Region (on SimaPro)
Intermediate resource	Wet nodule collected onto system at sea (total)			6.40	Mt	TMC	CCZ
	Wet nodule collected onto system at sea	MnSi (93%)		5.95	Mt	Calculated	CCZ
		Ni/Cu/Co (7%)		0.448			
Fuel	Bituminous coal (total)			474			
	Bituminous coal	Coal fraction - reduction (80%)	MnSi (62%)	235			
			Ni/Cu/Co (38%)	144			
		Fixed carbon inefficiencies - heat (20%)	MnSi (92.5%)	87.5			
			Ni/Cu/Co (7.5%)	7.10			

Production stage: Hydrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Materials	Oxygen, liquid (total)		104	kt	TMC	Rest of the World
	Oxygen, liquid	Ni (64%)	66.7	kt	Calculated	Rest of the World
		Cu (22%)	22.9	kt	Calculated	Rest of the World
		Co (14%)	14.6	kt	Calculated	Rest of the World
	Potassium hydroxide (total)		1610	t	TMC	Global
	Potassium hydroxide	Ni (64%)	1030	t	Calculated	Global
		Cu (22%)	354	t	Calculated	Global
		Co (14%)	226	t	Calculated	Global

Results overview

In this chapter, results from the life-cycle impact assessment (LCIA) of the five TMC NORI-D products are presented and analysed.

For each TMC NORI-D product:

- **Overall results of the midpoint and endpoint impact categories** are demonstrated to understand the environmental impacts introduced in each area of concern for a higher-level assessment.
- **Contributions of each production stage to Global Warming Potential (GWP)** are analysed to identify the highest carbon emissions hotspots
- **Contributions of each input to each of the impact categories** are assessed to identify the most polluting inputs

Overall Results – Manganese Silicate in Slag

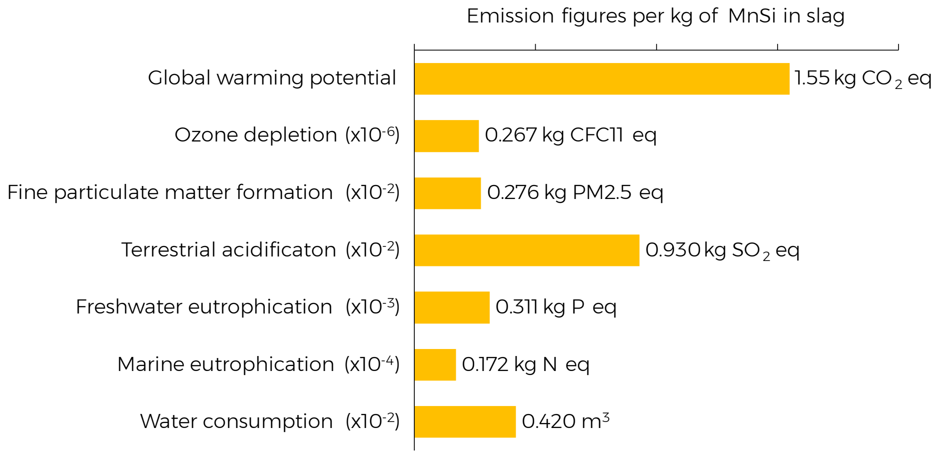
Slag containing manganese silicate (MnSi) is a co-product from the pyrometallurgical process.

In this section, the LCIA results for **1 kg of MnSi contained in slag** are analysed.

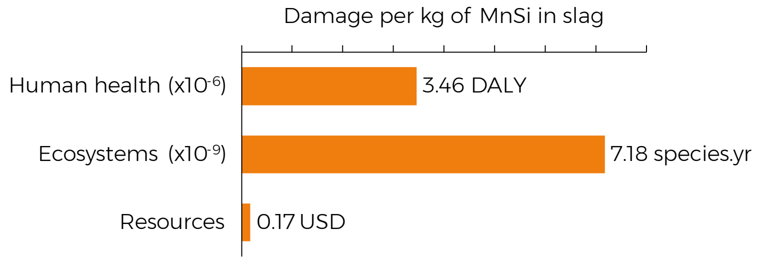
The results are computed from the 16 years of steady state production from the TMC NORI-D project (12.47 Mtpa of wet nodules equal to 9.47 Mtpa of dry nodules), and using an onshore flowsheet model representing a TMC nodule operation at a scale of 6.4 Mtpa of wet nodules.

The overall environmental impacts resulting from the production of 1 kg of MnSi in slag are demonstrated as the **emissions in each midpoint impact categories** (**in yellow**) and the **extent of damage in each areas of protection** (**in orange**).

Midpoint impact categories



Areas of protection



Please note that all LCIA results are corrected to 3 significant figures.

Contributions by production stage – Manganese Silicate in slag

Each impact category is affected differently by the processing steps. The contribution from the mining stage, for example, ranges from 22% to 41% of the total impact per category. Therefore each environmental impact is individually analysed (slide 33 and Appendix 2).

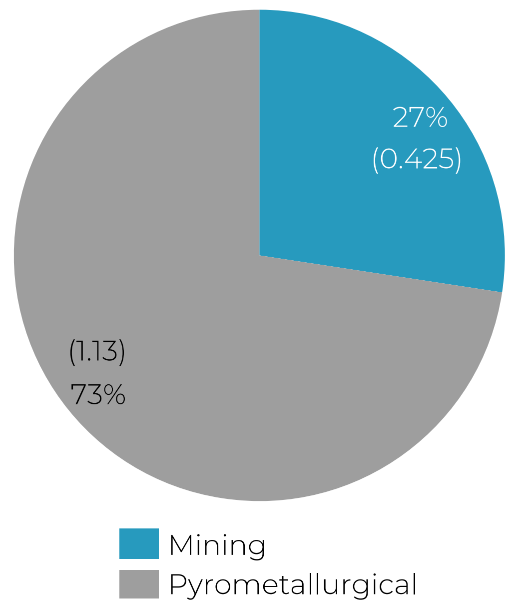
Due to possible trade-offs, where one product can be better in terms of carbon emissions but worst in eutrophication effects, it is important to look at the overall contribution through the possible impacts.

On the right hand side, a chart with the contributions of each production stage to GWP of MnSi in slag is provided.

About ¾ of the GHG emissions from the production of MnSi in slag is contributed by the pyrometallurgical process, with the remaining ¼ is contributed by mining.

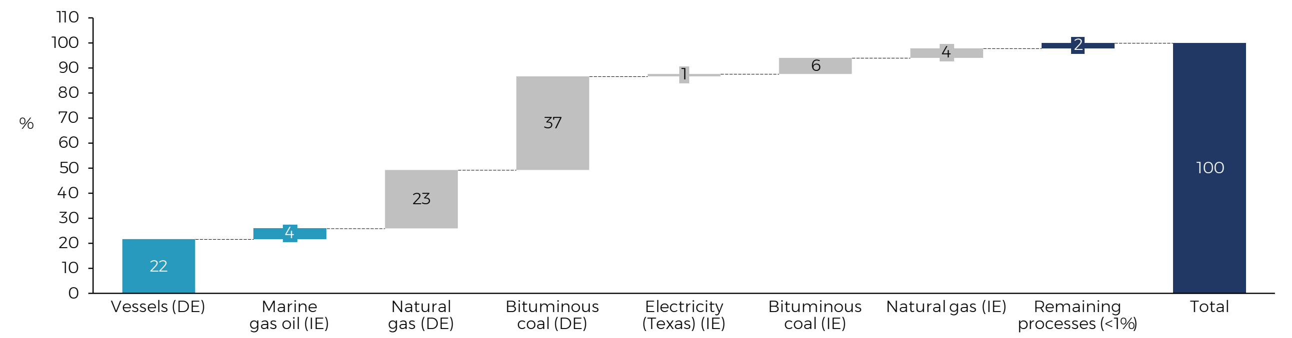
The input contribution graphs are colour coded with the **blue** bars representing the input contribution from mining and the **grey** representing the pyrometallurgical process.

Contribution to GWP by production stage
(Total = 1.55 kg CO_2 eq)



Input contributions for GWP – Manganese Silicate in slag

Total contribution per input (in %)



Contribution by stage

- Mining
- Pyrometallurgical
- All stages

Direct emissions (DE) are a result of on-site activities such as burning bituminous coal in the kiln.

Indirect emissions (IE) do not occur on-site, but are rather the upstream emissions from the production and distribution of inputs.

The vessel proxies such as transport and transshipment, also include life span, maintenance and disposal of vessels.

Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)	Terrestrial Acidification (x10^{-5} kg SO_2 eq)	Freshwater Eutrophication (x10^{-6} kg P eq)	Marine Eutrophication (x10^{-7} kg N eq)	Water Consumption (x10^{-5} m^3)
Vessels (DE)	0.334	0	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

The input contributions graphs and tables for the other six impact categories can be found in Appendix 2.

Interpretation: summary of the results – Manganese Silicate in Slag

The major contributors include bituminous coal, the production of marine gas oil and the direct emissions from mining.

1. Bituminous coal is the chief environmental hotspot. The direct emissions from burning bituminous coal in the kiln is one of the major contributors in 3 out of 7 impact categories, including GWP (37%), fine particulate matter formation (38%) and terrestrial acidification (40%).

2. The production and distribution of bituminous coal is the environmental hotspot in freshwater (69%) and marine eutrophication (76%), suggesting an opportunity to lower emissions by purchasing bituminous coal from less-polluting providers and/or find ways to replace coal as a reductant.

3. Nonetheless, since TMC is researching on the use of biomass pellets as fuels, among other alternatives, to lower the direct emissions. The emissions from bituminous coal could be avoided in operation if this happens. The benefits can be disclosed once data is available.

4. The second highest contributor to greenhouse gases (GHG) emissions is the direct emissions from burning **natural gas** (for heat) which would potentially become the highest contributor if coal is replaced by biomass pellets in the future or other lower emissions alternative. Hence, efforts should be directed to preventing heat losses and using alternative low-carbon fuels. In terms of GWP specifically, **direct** emissions are the greatest contributors. Aside from lowering direct emissions from heat production, efforts should also be directed to lowering the direct emissions from mining offshore.

5. Although direct water usage is the environmental hotspot in water consumption, most water used evaporates and returns to the natural cycle. The overall water consumption is minor (0.00420 m^3 per kg of MnSi in slag).

6. At a higher level, the damage to human health is mainly attributed to GHG and sulphur dioxide emissions. In terms of ecosystems damage and resources exploitation, the GHG emissions from terrestrial ecosystems (such as the mining step and bituminous coal direct emissions) and fossil resource scarcity are respectively the highest contributors.

Overall Results – Ni/Cu/Co in Matte

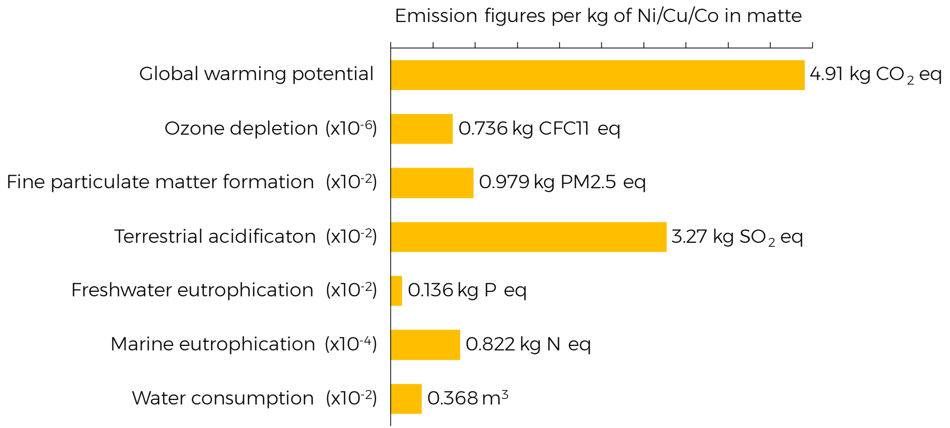
Nickel, copper and cobalt contained in matte are the products from the pyrometallurgical process.

In this section, the LCIA results for **1 kg of Ni/Cu/Co contained in matte** are analysed.

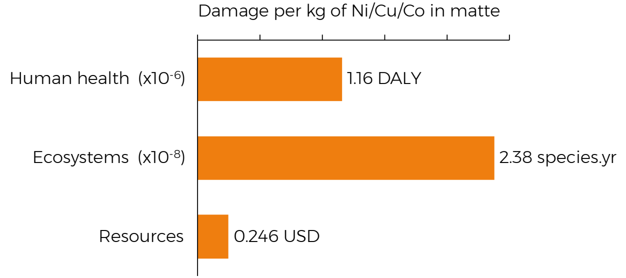
The results are computed from the 16 years of steady state production from the TMC NORI-D project (12.47 Mtpa of wet nodules equal to 9.47 Mtpa of dry nodules) and using an onshore flowsheet model representing a TMC nodule operation at a scale of 6.4 Mtpa of wet nodules.

The overall environmental impacts resulting from the production of 1 kg of Ni/Cu/Co in matte are demonstrated as the **emissions in each midpoint impact categories** (**in yellow**) and the **extent of damage in each areas of protection** (**in orange**).

Midpoint impact categories



Areas of protection



Please note that all LCIA results are corrected to 3 significant figures.

Contributions by production stage – Ni/Cu/Co in matte

Each impact category is affected differently by the processing steps. The contribution from the mining stage, for example, ranges from 7% to 11% of the total impact per category. Therefore each environmental impact is individually analysed (slide 37 and Appendix 3).

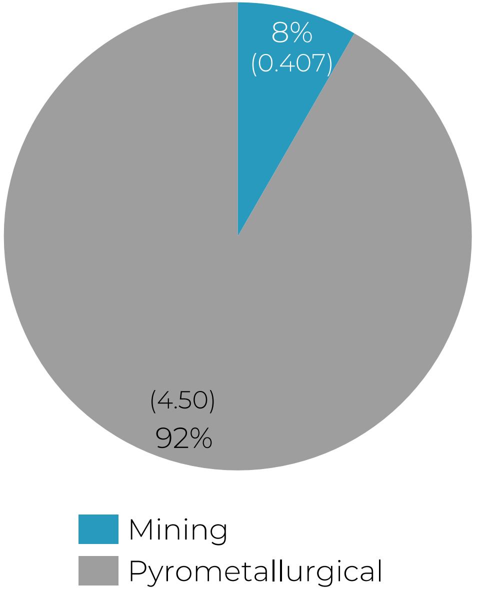
Due to possible trade-offs, where one product can be better in terms of carbon emissions but worst in eutrophication effects, it is important to look at the overall contribution through the possible impacts.

On the right hand side, a chart with the contributions of each production stage to GWP of Ni/Cu/Co in matte is provided.

The majority of the GHG emissions (92%) of the production of Ni/Cu/Co in matte are a result of the pyrometallurgical process while mining contributed to less than 10% of the overall GHG emissions.

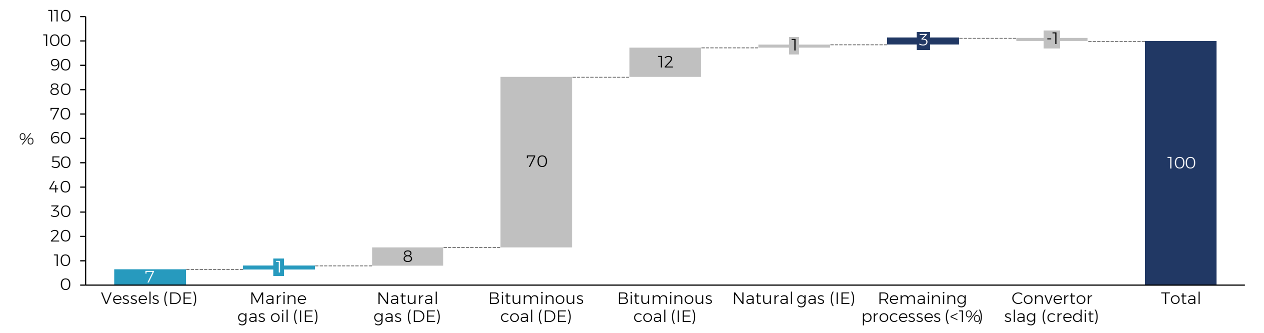
The input contribution graphs are colour coded with the **blue** bars representing the input contribution from mining and the **grey** representing the pyrometallurgical process.

Contribution to GWP by production stage (Total = 4.91 kg CO_2 eq)



Input contributions for GWP – Ni/Cu/Co in matte

Total contribution per input (in %)



Contribution by stage

- Mining
- Pyrometallurgical
- All stages

Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-6} kg N eq)	Water Consumption (x10^{-5} m^3)
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

Direct emissions (DE) are a result of on-site activities such as burning bituminous coal in the kiln.

Indirect emissions (IE) do not occur on-site, but are rather the upstream emissions from production and distribution of inputs.

The vessel proxies such as transport and transshipment, also include life span, maintenance and disposal of vessels.

The input contributions graphs and tables for the other six impact categories can be found in Appendix 3.

* represents less than 1%, included in the remaining process (1% cut-off)

Interpretation: summary of the results – Ni/Cu/Co in Matte

Bituminous coal is evidently the greatest contributor to all the environmental impacts except in water consumption since pyrometallurgical process is the most significant step. Its contribution ranges from 56% to 94%, while the contributions from the second highest contributor in the same impact categories only ranges from 4% to 14%.

1. Similar to the production of MnSi in slag, the direct emissions from **combusting coal** in the kiln is the major contributor in 4 out of 7 impact categories: GWP (70%), ozone depletion (56%), fine particulate matter formation (64%) and terrestrial acidification (65%).

2. Additionally, **the production and distribution of bituminous coal** contribute to 94% of freshwater and marine eutrophication potentials, proposing the need to purchase bituminous coal from less-polluting suppliers and/or find ways to replace coal as a reductant.

3. At the aggregated level, the main contributor to the damage of human health and ecosystems comes from the direct emissions of burning bituminous coal. Fossil resource scarcity is the main contributor to the exploitation of natural resources.

4. Since TMC is researching the use of biomass pellets as alternative fuels, among other alternatives, there is a great emissions reduction potential if bituminous coal is replaced in operations. In that case, the main contributor would switch from direct emissions to indirect emissions (e.g. sulphuric acid and ammonia - production and distribution).

5. Although direct water usage is the environmental hotspot within the water consumption impact category, most water used evaporates and returns to the natural cycle. The overall water consumption is minor (0.00380 m3 per kg of Ni/Cu/Co in matte).

6. The impact of convertor slag production as a by-product is limited in most categories where only up to 5% of the total emissions are avoided. However, the effects of environmental credit are more prominent in saving water consumption (-46%).

Overall Results – Nickel in Nickel Sulphate

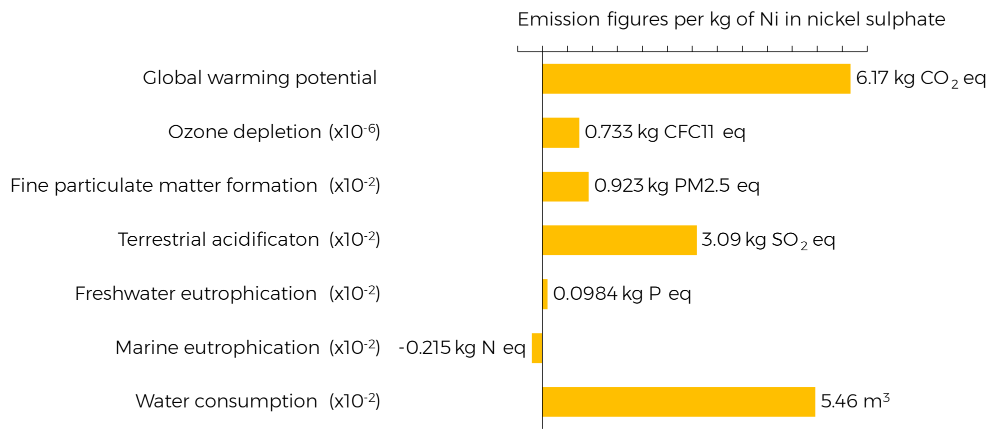
Nickel (Ni) contained in nickel sulphate ($NiSO_4.6H_2O$) is one of the main products from the hydrometallurgical process.

In this section, the LCIA results for **1 kg of Ni in nickel sulphate** are analysed.

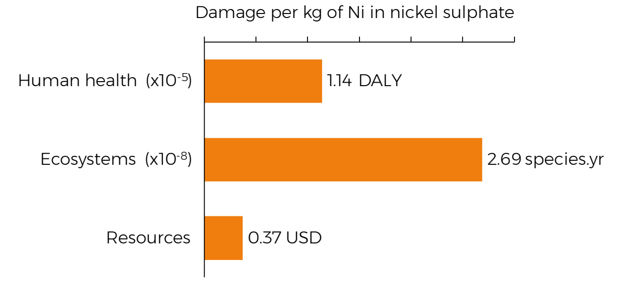
The results are computed from the 16 years of steady state production from the TMC NORI-D project (12.47 Mtpa of wet nodules equal to 9.47 Mtpa of dry nodules), and using an onshore flowsheet model representing a TMC nodule operation at a scale of 6.4 Mtpa of wet nodules.

The overall environmental impacts resulting from the production of 1 kg of Ni in nickel sulphate are demonstrated as the **emissions in each midpoint impact categories** (**in yellow**) and the **extent of damage in each areas of protection** (**in orange**).

Midpoint impact categories



Areas of protection



Please note that all LCIA results are corrected to 3 significant figures.

Contributions by production stage – Nickel in Nickel Sulphate

Each impact category is affected differently by the processing steps. The contribution from the mining stage, for example, ranges from 6% to 14% of the total impact per category. Therefore each environmental impact is individually analysed (slide 41 and Appendix 4).

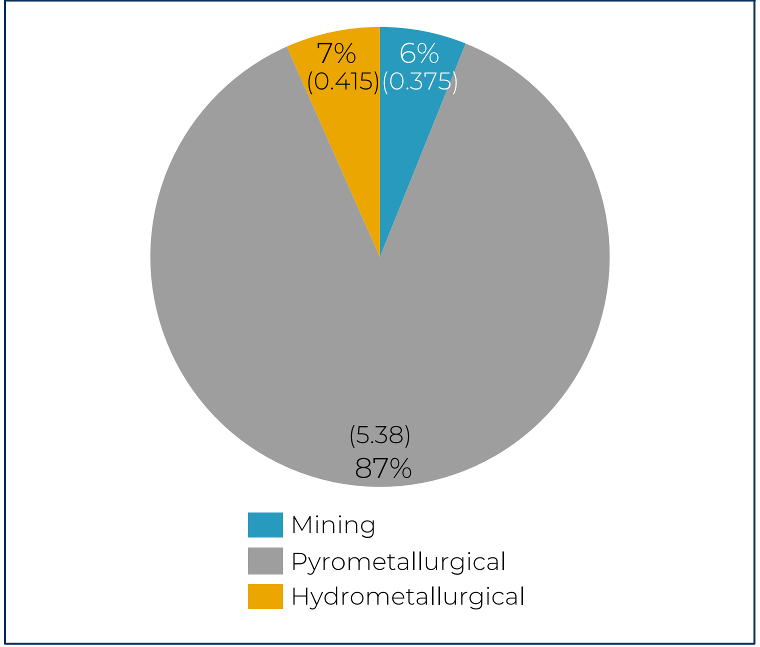
Due to possible trade-offs, where one product can be better in terms of carbon emissions but worst in eutrophication effects, it is important to look at the overall contribution through the possible impacts.

On the right hand side, a chart with the contributions of each production stage to GWP of Ni in nickel sulphate is provided.

The GHG emissions from the production of Ni in nickel sulphate are dominated by the pyrometallurgical process accounting for 87% of the total GWP. Meanwhile, the contributions of the hydrometallurgical process and mining stage are much lower at 6% and 7% respectively and highly similar.

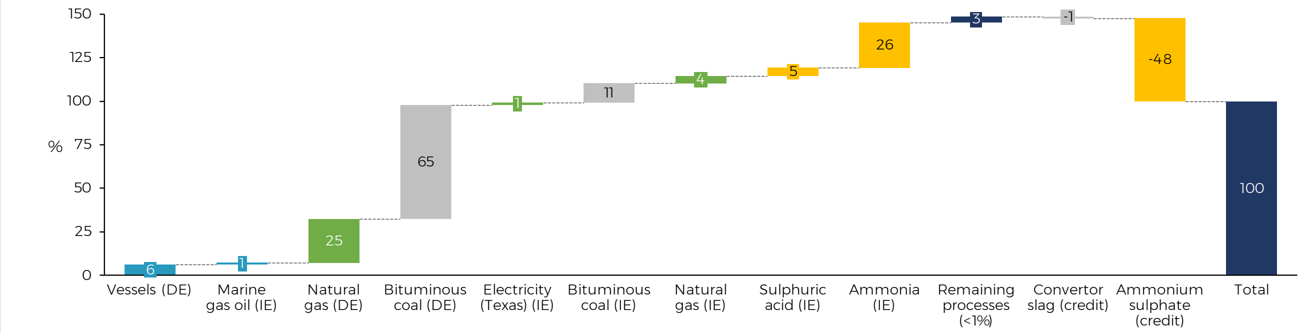
The input contribution graphs are colour coded with the **blue** bars representing the input contribution from mining and the **grey** representing the pyrometallurgical process and **orange** illustrating hydrometallurgical inputs.

Contribution to GWP by production stage
(Total = 6.17 kg CO_2 eq)



Input contributions for GWP – Nickel in Nickel Sulphate

Total contribution per input (in %)



Contribution by stage

- Mining
- Pyrometallurgical
- Hydrometallurgical
- Both onshore stages
- All stages

Direct emissions (DE) are a result of on-site activities such as burning bituminous coal in the kiln.

Indirect emissions (IE) do not occur on-site, but are rather the upstream emissions from production and distribution of inputs.

Input contribution (in absolute values)

	GWP (kg CO$_2$ eq)	Ozone Depletion (x10^{-8} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO$_2$ eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-5} kg N eq)	Water Consumption (x10^{-3} m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

The input contributions graphs and tables for the other six impact categories can be found in Appendix 4.

* represents less than 1%, included in the remaining process (1% cut-off)

Interpretation: summary of the results – Nickel in Nickel Sulphate

Direct emissions from bituminous coal and natural gas, as well as the productions of sulphuric acid and ammonia are hotspots among the impact categories analysed.

1. Bituminous coal is the most significant contributor to every impact category analysed, except for water consumption and marine eutrophication. TMC is studying a biomass pellet, among other alternatives, to lower direct emissions. This material is not considered in this analysis and it is suggested that the benefits are disclosed by the company once data is available.

2. The direct emissions from burning **natural gas** for heat is the second highest contributor to GHG emissions. The prevention of heat losses and alternative technology is recommended. Because of the direct combustion of fossil fuels onshore, **Direct emissions** are the greatest contributor to GHG emissions.

3. The impacts of sulphuric acid and ammonia production are influenced by the choice of suppliers. In the analysis, a global average is used, hence a part of Asian suppliers relying on dirtier electricity mixes is considered within the results. It is recommended that TMC chooses its suppliers with the same level of environmental consciousness as their own operations.

4. The direct water use in TMC's operations are responsible for more than half of the impact in the category. TMC states that the water will be sourced from the municipality. Benchmark suggests looking at alternative sources such as wastewater recycled.

5. The avoided emissions from convertor slag are limited with up to 5% savings only. Nonetheless, the avoided emissions from ammonium sulphate are much greater, which offers 48-172% emissions savings across the different impact categories, more than the direct burdens from the greatest contributors. Consequently, accounting for environmental credit is impactful on the overall emissions in all impact categories in the production of nickel in nickel sulphate.

6. At a higher level, direct emissions from coal are the major contribution to the damage of ecosystems and human health. Fossil fuel scarcity is the category with the most impact on resources exploitation.

Overall Results – Copper cathode

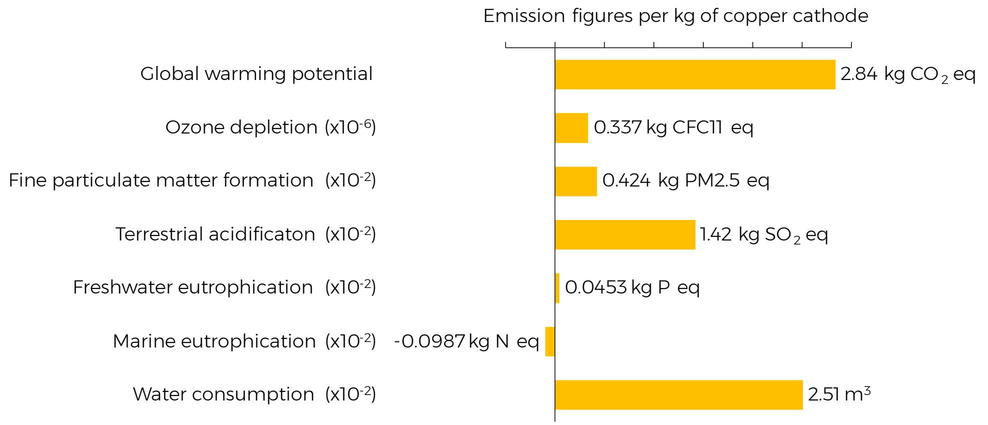
Copper (Cu) cathode is one of the main products from the hydrometallurgical process.

In this section, the LCIA results for **1 kg of copper cathode** are analysed.

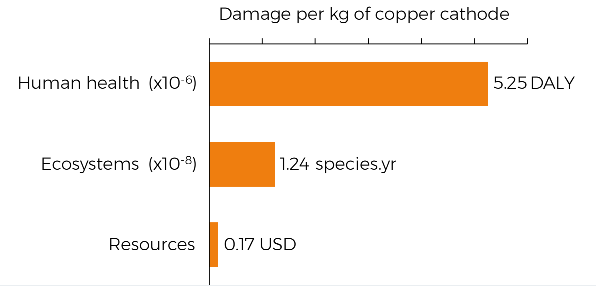
The results are computed from the 16 years of steady state production from the TMC NORI-D project (12.47 Mtpa of wet nodules equal to 9.47 Mtpa of dry nodules), and using an onshore flowsheet model representing a TMC nodule operation at a scale of 6.4 Mtpa of wet nodules in TMC.

The overall environmental impacts resulting from the production of 1 kg copper cathode are demonstrated as the **emissions in each midpoint impact categories** (**in yellow**) and the **extent of damage in each areas of protection** (**in orange**).

Midpoint impact categories



Areas of protection



Please note that all LCIA results are corrected to 3 significant figures.

Contributions by production stage – Copper cathode

Each impact category is affected differently by the processing steps. The contribution from the mining stage, for example, ranges from 6 to 14% of the total impact per category. Therefore each environmental impact is individually analysed (slide 45 and Appendix 5).

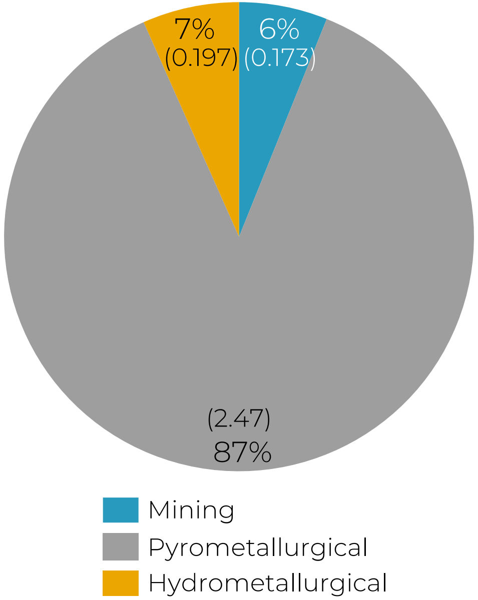
Due to possible trade-offs, where one product can be better in terms of carbon emissions but worst in eutrophication effects, it is important to look at the overall contribution through the possible impacts.

On the right hand side, a chart with the contributions of each production stage to GWP of copper cathode is provided.

Although the GWP of copper cathode production is 2 times lower than that of Ni in nickel sulphate production, the contributions to GWP by production stage of the two products are the same, with the pyrometallurgical process being the most polluting stage accounting for 87% of the total GWP.

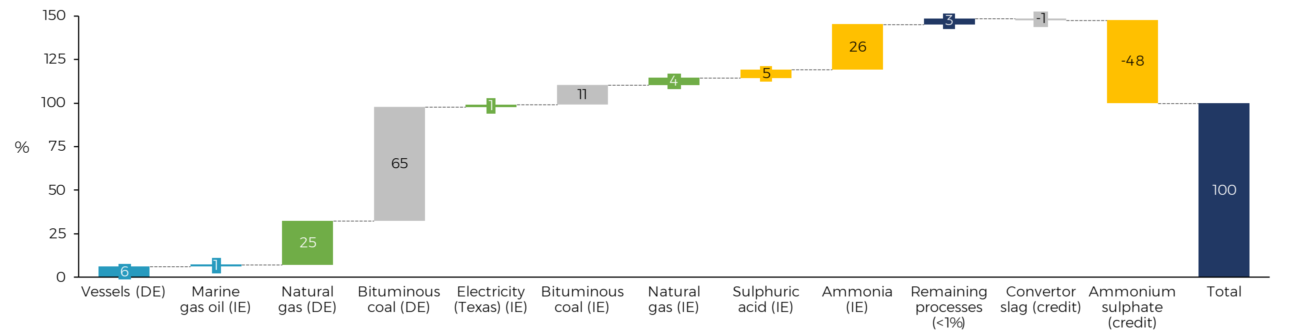
The input contribution graphs are colour coded with the **blue** bars representing the input contribution from mining and the **grey** representing the pyrometallurgical process and **orange** illustrating hydrometallurgical inputs

Contribution to GWP by production stage
(Total = 2.84 kg CO_2 eq)



Input contributions for GWP – Copper cathode

Total contribution per input (in %)



Contribution by stage

- Mining
- Pyrometallurgical
- Hydrometallurgical
- Both onshore stages
- All stages

Direct emissions (DE) are a result of on-site activities such as burning bituminous coal in the kiln.

Indirect emissions (IE) do not occur on-site, but are rather the upstream emissions from the production and distribution of inputs.

The input contributions graphs and tables for the other six impact categories can be found in Appendix 5.

Input contribution (in absolute values)

	GWP (kg CO_2 eq)	**Ozone Depletion ($x10^{-9}$ kg CFC11 eq)**	**Fine Particulate Matter Formation ($x10^{-5}$ kg PM2.5 eq)**	**Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)**	**Freshwater Eutrophication ($x10^{-6}$ kg P eq)**	**Marine Eutrophication ($x10^{-5}$ kg N eq)**	**Water Consumption ($x10^{-4}$ m^3)**
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Interpretation: summary of the results – Copper Cathode

Direct emissions from bituminous coal and natural gas, as well as the productions of sulphuric acid and ammonia are hotspots among the impact categories analysed.

1. Bituminous coal is the most significant contributor to every impact category analysed, except for water consumption and marine eutrophication. TMC is studying a biomass pellet, among other alternatives, to lower direct emissions. This material is not considered in this analysis and it is suggested that the benefits are disclosed by the company once data is available.

2. The direct emissions from burning natural gas for heat is the second highest contributor to GHG emissions. The prevention of heat losses and alternative technology is recommended. Because of the direct combustion of fossil fuels onshore. Direct emissions are is the greatest contributor to GHG emissions.

3. The impacts of sulphuric acid and ammonia production are influenced by the choice of suppliers. In the analysis, a global average is used, hence a part of Asian suppliers relying on dirtier electricity mixes is considered within the results. It is recommended that TMC chooses its suppliers with the same level of environmental consciousness as their own operation.

4. The direct water use in TMC's operations are responsible for more than half of the impact in the category. TMC states that the water will be sourced from the municipality. Benchmark suggests looking at alternative source such as wastewater recycled.

5. The avoided emissions from convertor slag are limited with up to 5% savings only. Nonetheless, the avoided emissions from ammonium sulphate are much greater, which offers 48-172% emissions savings across the different impact categories, more than the direct burdens from the greatest contributors. Consequently, accounting for environmental credit is impactful on the overall emissions in all impact categories in the production of copper cathode.

6. At a higher level, direct emissions from coal are the major contribution to the damage of ecosystems and human health. Fossil fuel scarcity is the category with the most impact on resources exploitation.

Overall Results – Cobalt in Cobalt Sulphate

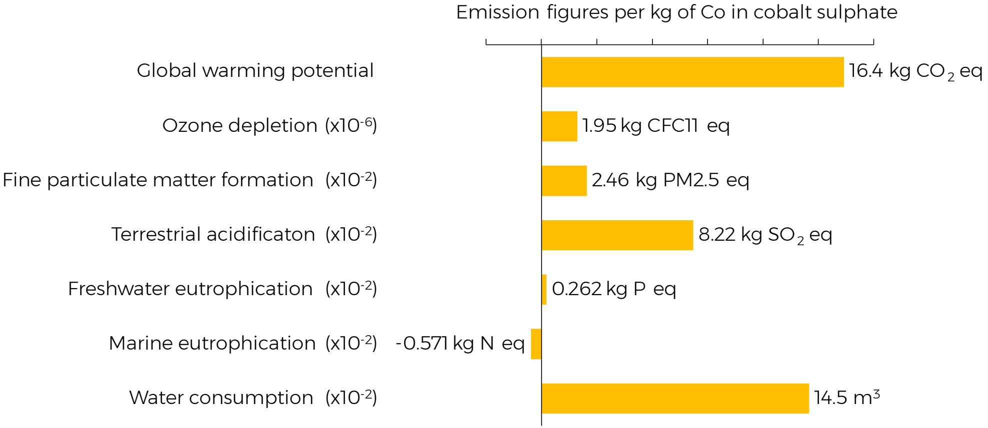
Cobalt (Co) contained in cobalt sulphate ($CoSO_4.7H_2O$) is one of the main products from the hydrometallurgical process.

In this section, the LCIA results for **1 kg of Co in cobalt sulphate** are analysed.

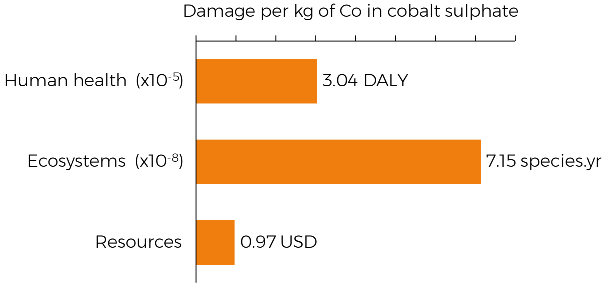
The results are computed from the 16 years of steady state production from the TMC NORI-D project (12.47 Mtpa of wet nodules equal to 9.47 Mtpa of dry nodules), and using an onshore flowsheet model representing a TMC nodule operation at a scale of 6.4 Mtpa of wet nodules.

The overall environmental impacts resulting from the production of 1 kg of Co in cobalt sulphate are demonstrated as the **emissions in each midpoint impact categories** (**in yellow**) and the **extent of damage in each areas of protection** (**in orange**).

Midpoint impact categories



Areas of protection



Please note that all LCIA results are corrected to 3 significant figures.

Contributions by production stage – Cobalt in Cobalt Sulphate

Each impact category is affected differently by the processing steps. The contribution from the mining stage, for example, ranges from 6% to 16% of the total impact per category. Therefore each environmental impact is individually analysed (slide 49 and Appendix 6).

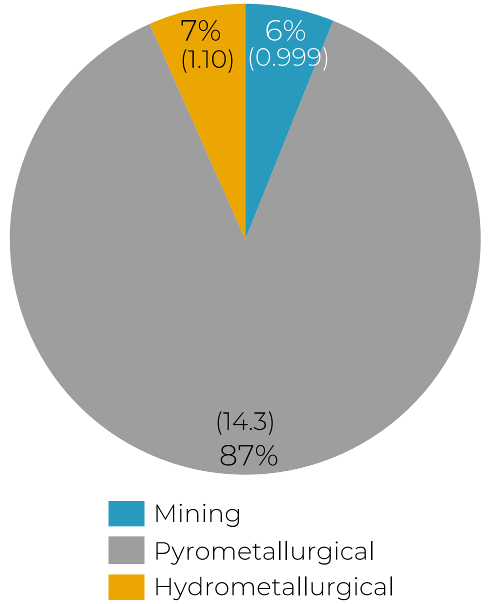
Due to possible trade-offs, where one product can be better in terms of carbon emissions but worst in eutrophication effects, it is important to look at the overall contribution through the possible impacts.

On the right hand side, a chart with the contributions of each production stage to GWP of cobalt in cobalt sulphate is provided.

The percentage contributions of each production stage of cobalt sulphate are highly similar to the previous two products, i.e. nickel in nickel sulphate and copper cathode, despite its production releasing a greater amount of GHG emissions into the atmosphere (2.66 and 5.77 times higher respectively).

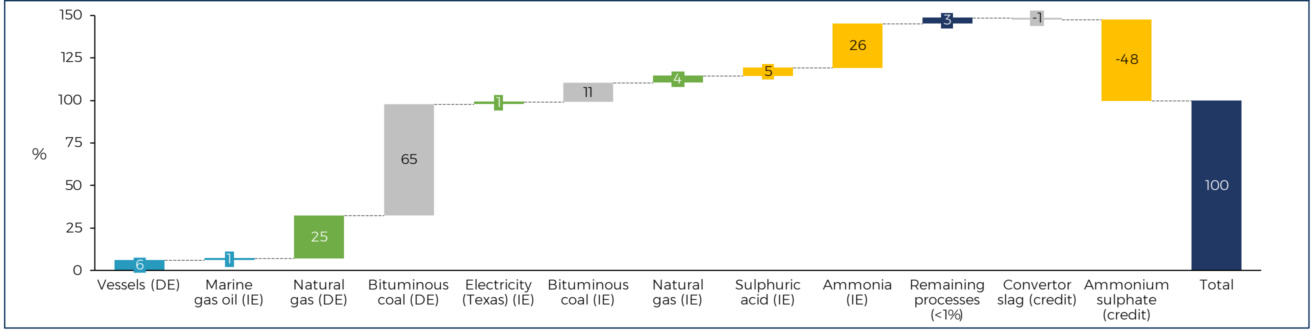
The input contribution graphs are colour coded with the **blue** bars representing the input contribution from mining and the **grey** representing the pyrometallurgical process and **orange** illustrating hydrometallurgical inputs.

Contribution to GWP by production stage
(Total = 16.4 kg CO_2 eq)



Input contributions for GWP – Cobalt in Cobalt Sulphate

Total contribution per input (in %)



Contribution by stage

- Mining
- Pyrometallurgical
- Hydrometallurgical
- Both onshore stages
- All stages

Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

Direct emissions (DE) are a result of on-site activities such as burning bituminous coal in the kiln.

Indirect emissions (IE) do not occur on-site, but are rather the upstream emissions from the production and distribution of inputs.

The input contributions graphs and tables for the other six impact categories of can be found in Appendix 6.

* represents less than 1%, included in the remaining process (1% cut-off)

Interpretation: summary of the results – Cobalt in Cobalt Sulphate

Direct emissions from bituminous coal and natural gas, as well as the productions of sulphuric acid and ammonia are hotspots among the impact categories analysed.

1. Bituminous coal is the most significant contributor to every impact category analysed, except for water consumption and marine eutrophication. TMC is studying a biomass pellet, among other alternatives, to lower direct emissions. This material is not considered in this analysis and it is suggested that the benefits are disclosed by the company once data is available.

2. The direct emissions from burning natural gas for heat is the second highest contributor to GHG emissions. The prevention of heat losses and alternative technology is recommended. Because of the direct combustion of fossil fuels onshore, Direct emissions are the greatest contributor to GHG emissions.

3. The impacts of sulphuric acid and ammonia production are influenced by the choice of suppliers. In the analysis, a global average is used, hence a part of Asian suppliers relying on dirtier electricity mixes is considered within the results. It is recommended that TMC chooses its suppliers with the same level of environmental consciousness as their own operation

4. The direct water use in TMC's operations are responsible for more than half of the impact in the category. TMC states that the water will be sourced from the municipality. Benchmark suggests looking at alternative source such as wastewater recycled.

5. The avoided emissions from convertor slag are limited with up to 5% savings only. Nonetheless, the avoided emissions from ammonium sulphate are much greater, which offers 48-172% emissions savings across the different impact categories, more than the direct burdens from the greatest contributors. Consequently, accounting for environmental credit is impactful on the overall emissions in all impact categories in the production of cobalt in cobalt sulphate.

6. At a higher level, direct emissions from coal are the major contribution to the damage of ecosystems and human health. Fossil fuel scarcity is the category with the most impact on resources exploitation.

Sensitivity analysis

The purpose of a sensitivity analysis is to investigate the effects of changes in parameters' input on the results and to reassure the robustness of the methodology and results. The sensitivity analysis then informs the recommendations of the LCA.

The following analyses focuses on a few sources of uncertainty concerning the model which are highlighted.

1) Location: Texas versus other possible regions for onshore processing

   i. Texas: based on 100% **wind** energy, **7 vessels** for transshipment, **3,683 nautical miles** port-to-port
   ii. India: Captive **solar** scenarios with Energy Storage System (ESS), **9 vessels** for transshipment, **9,500 nautical miles** port-to-port
   iii. Malaysia: based on 100% **hydro** power, **8 vessels** for transshipment, **7,300 nautical miles** port-to-port

2) Metal price variation: 10-year average versus 2022 prices

3) Environmental credit: ammonium sulphate credit via system expansion versus co-production

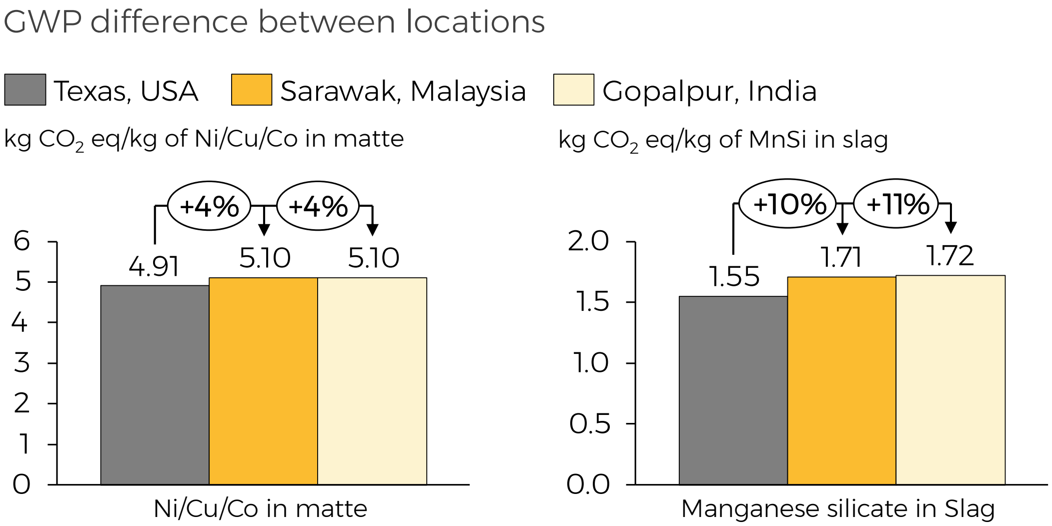
4) Allocation within the pyrometallurgical step: current allocation versus total economic allocation

The variations are compared to TMC NORI-D's scenario, this enables the comparison of input changes, therefore defining parameters' sensitivity and ranking influence. Throughout the sensitivity analysis it is possible to determine the influence of parameter uncertainties.

Sensitivity analysis 1) location

To better inform the client about the decision of the location for the onshore operation, the following slides look closer to the differences between the possible regions. The graphs below show minimum changes to GWP which demonstrated that location is not a hotspot for this impact.

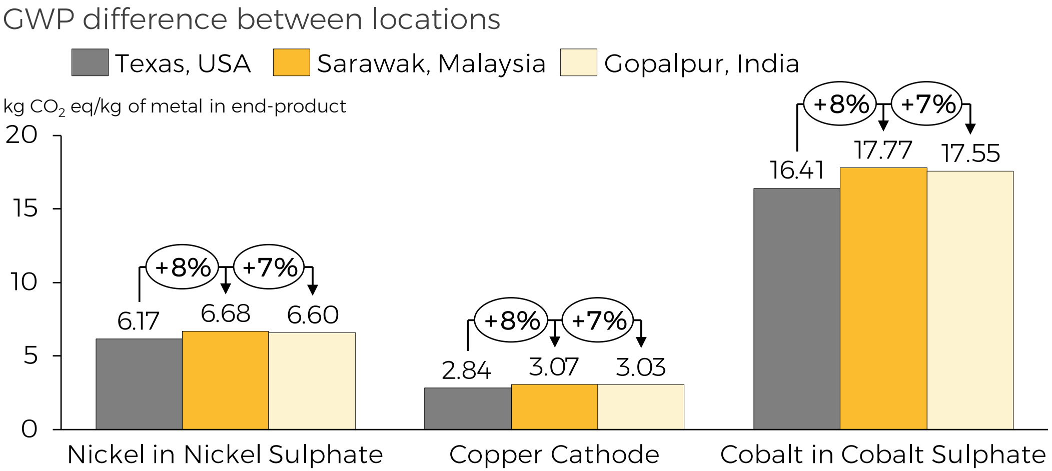
The Ni/Cu/Co matte is an intermediate product of which Manganese silicate (MnSi) is a co-product in the pyrometallurgical stage. Both mining and pyrometallurgy are included in the results.



Sensitivity analysis 1) location

Nickel sulphate, copper cathode and cobalt sulphate are products obtained after the hydrometallurgical stages. Here location will determine the electricity source, but impact assessment carries the upstream emissions as well.

The bars below represent the overall impact differences in GWP between the different locations throughout TMC's wet nodule processing (mining, pyrometallurgy and hydrometallurgy).



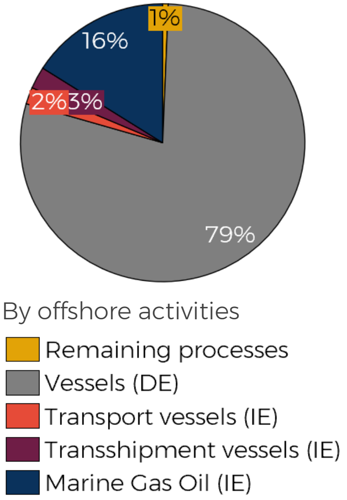
Sensitivity analysis 1) location

The direct exhaust emissions (DE) from the vessels (mining, transport, survey, support and transshipment) contribute to 79% of the GWP impact. Whilst, the indirect emissions (IE) from production and distribution of marine gas oil consumption represent 16% of the overall GWP to collect 1 kg of wet nodule.

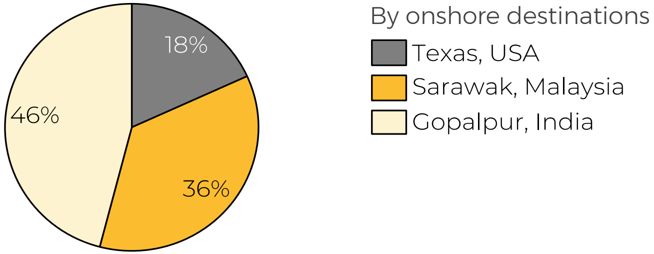
The location where the nodules need to be transported for onshore processing is not the hotspot, because transshipment represents 27% of the overall fuel consumption on offshore operations as compared to 45% of fuel for the mining vessels (nodule collection and vessel repositioning).

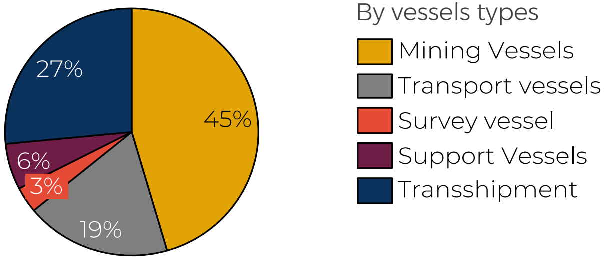
The impact of transshipment is influenced by location as it is determined by the distance between ports and number of vessels need for transshipment vary accordingly. According to the breakdown of fuel consumption by onshore destinations, Texas would require the lowest amount of marine gas oil.

Offshore GWP breakdown – 1 kg of wet nodule

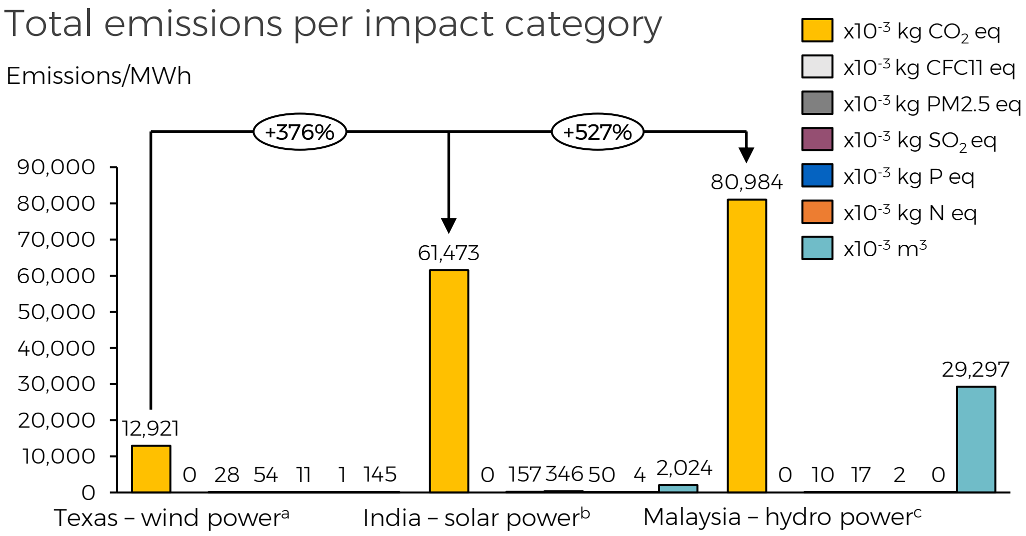


Offshore fuel consumption breakdown





Sensitivity analysis 1) location



The graph on the left provides a closer look at the impacts from each electricity source proxy. The hydro power from Malaysia has the highest GWP impact.

Although small, the impact of renewable energy sources is not null. The highest contribution to GHG emissions is often traced back to the infrastructure of the power plant.

In wind turbines, the pig iron production of steel is the major contributor. For solar power, silicon in the cell production is the hotspot. Whereas in hydropower plant, emissions come from running the plant, direct impact, which has been been measured from 55 data points[1].

[a] Electricity, high voltage {TRE}| electricity production, wind, 1-3MW turbine, onshore | Cut-off, S
[b] Electricity, low voltage {IN-WB}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, S
[c] Electricity, high voltage {MY}| electricity production, hydro, reservoir, tropical region | Cut-off, U

1. *Hertwich, E.G., 2013. Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA. Environmental Sciency&Technology, (47), pp. 9604-9611.*

Sensitivity analysis 2) metal price variation

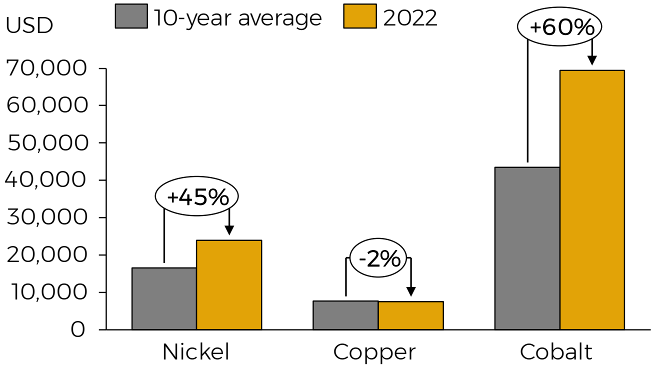
The environmental burden of the hydrometallurgical process is economically allocated between its co-products, meaning that the share of the impacts related to this stage depends not only on the volume of production but also on the price of these materials. Due to high variability in prices of the metals analysed, a 10-year average is adopted in TMC NORI-D model.

The bar graph on the left, compares the 10-year price average of these metals to 2022 prices. Cobalt has the highest difference between the two values with a 60% increase, followed by Nickel with a 45% increase and for Copper there is a decrease of 2%. In the graph, we have seen the results mirror the cost of material: cobalt is the most expensive material, followed by nickel and then copper as the cheapest in comparison.

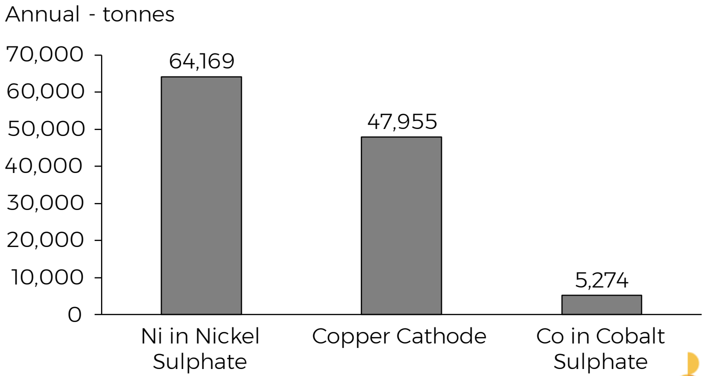
The volume of production (annual numbers on the right bar graph) dictate the sovereignty of nickel in the process which along with the price is a key economic driver of the project. Nickel is the leading material produced in the hydrometallurgical step, excluding manganese silicate at the previous stage.

Since the same pattern in price is observed, value hierarchy between metals is maintained, and the volume production doesn't change, it is expected that this variation will not significantly affect the emissions performances analysed.

Price difference between 10-year average and 2022 values



TMC NORI-D annual hydrometallurgical production volume



Sensitivity analysis 2) metal price variation

As expected from the observations in price and volume (prior slide) the overall results are only slightly affected when using the 10-year price average vs. 2022 prices. Additionally, the results proportion between the metals remaining similar.

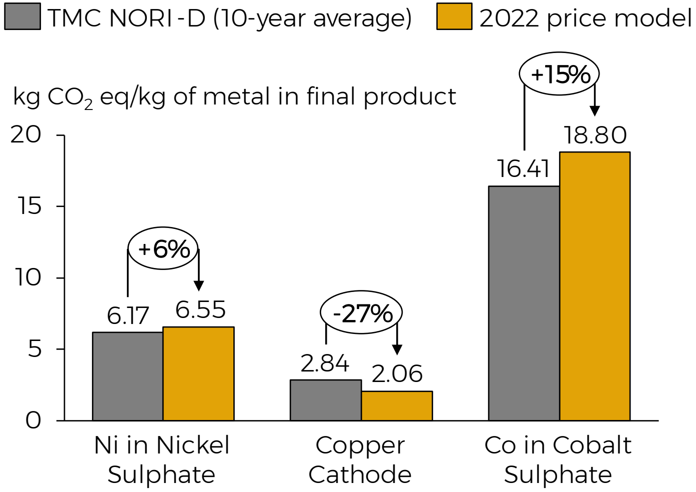
GWP results from adopting 2022 prices model show some differences per end-product metal as compared with those obtained from the 10-year price average. These changes tend to mimic the price trend: 15% and 6% GWP impact increase for cobalt and nickel from a price increase of 60% and 45%, respectively.

GWP impact for copper drops by 27% although its 2022 price is only 2% lower than the 10-years average. This is because, as the copper price decreases, the price of cobalt and nickel increase, making the share of the environmental burden attributed to copper production lower.

This sensitivity analysis suggests that metal price is a parameter that effects the GWP results. This, therefore, indicates that the methodological choice for price selection is important and result in uncertainty within methodological decisions.

However, due to overall effect in results, it is deemed minor to the interpretation of the impacts.

GWP difference between price variations



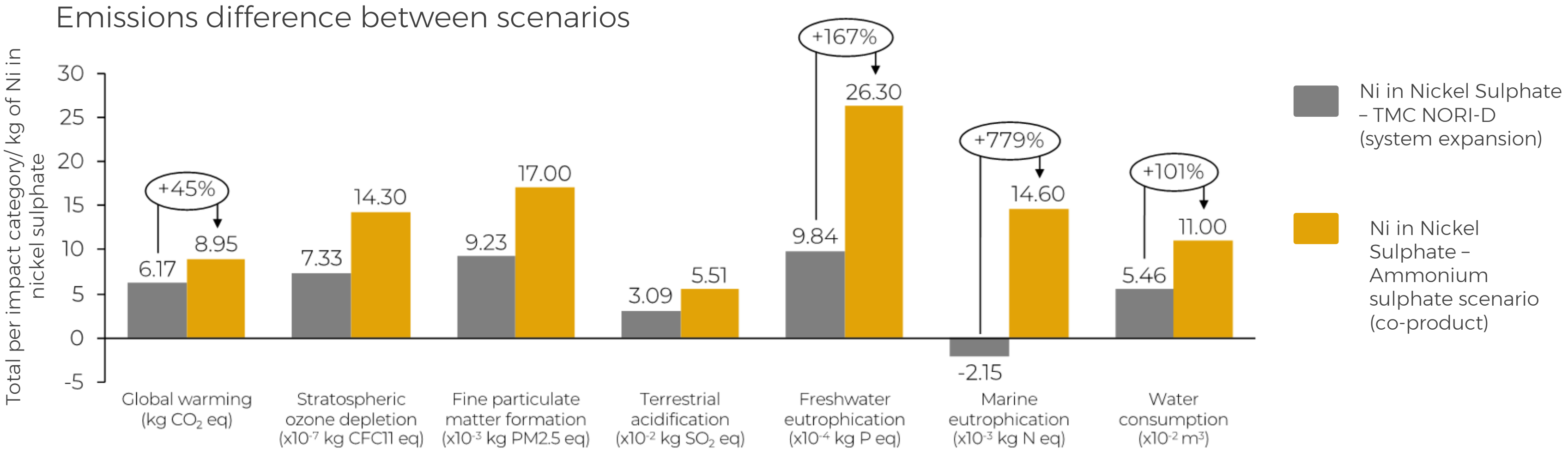
Sensitivity analysis 3) environmental credit

The industry and literature[1,2] defend that, as a by-product with low economic value, ammonium sulphate should be modelled through system expansion. ISO suggests system expansion as a way to avoid allocation.

However, as the input contribution graphs show, the ammonium sulphate credit varies largely between the impact categories ranging from -48% in GWP (slide 41) to -172% in freshwater eutrophication (slide 167).

Therefore, it is important to highlight the effect of this methodological choice. In the **ammonium sulphate scenario an economical allocation of 1% is adopted** which is the worst-case scenario based in the highest price and TMC NORI-D's volume of production. Consequently, nickel equal to 63%, copper 22%, and cobalt 14%, following the same methodological rule as the main model – 10-year average and volume of production.

As shown in the graph below, all impact categories are impacted by the ammonium sulphate credit in particular marine eutrophication, which is largely affected by the credit, indicating that, to understand the true impacts of the operation, the environmental credit must be transparently shown when disclosing results.



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1. *Santero and Hendry, 2016. Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.*
2. *Nickel Institute, 2022. How to determine GHG emissions from nickel metal Class 1: A guide to calculate nickel's carbon footprint.*

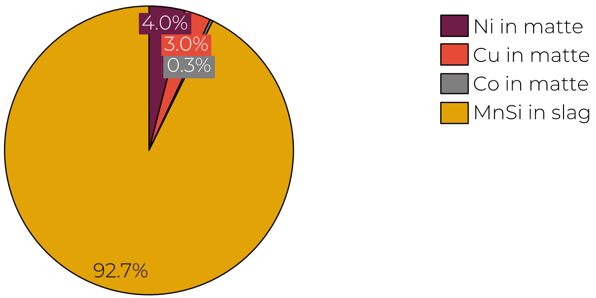
Sensitivity analysis 4) allocation within the pyrometallurgical step

It is widely discussed in the LCA community that mass allocation does not capture the economic purpose of obtaining multiple metals. **“Revenue is the driving force behind industrial operations”**[1].

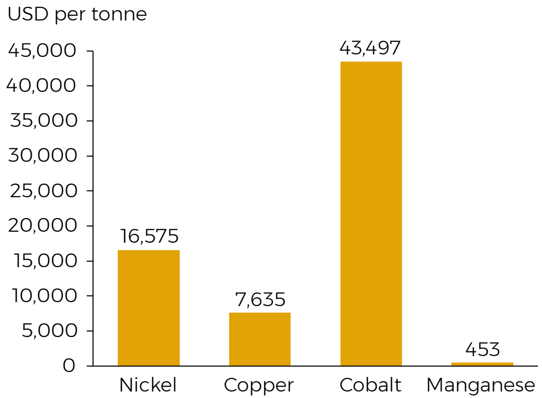
There is a debate on whether allocation per volume produced is fair when the metal content is known. **There is no right or wrong answer.** ISO standards provide a general framework for methodology, where allocation should be avoided, if possible, but it is constantly discussed that each LCA should be addressed as a case-by-case basis. However, addressing each case is not feasible due to the numerous technological differences in metal processing. Therefore, **harmonisation** of methodological choices is advised.

The industry suggests that for base metals (such as nickel, copper, cobalt) with significant price difference, economic allocation should be considered[1]. The Nickel Institute[2], on the other hand, advises that base metals do not have a “vast physical and economical difference”. However, as the charts here illustrate, the first statement seems appropriate to TMC’s production due to the difference in volume produced and the price of these metals in study.

TMC NORI-D pyrometallurgical production volume



Price per tonne of the product



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1. Santero and Hendry, 2016. Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.

2. Nickel Institute, 2022. How to determine GHG emissions from nickel metal Class 1: A guide to calculate nickel’s carbon footprint.

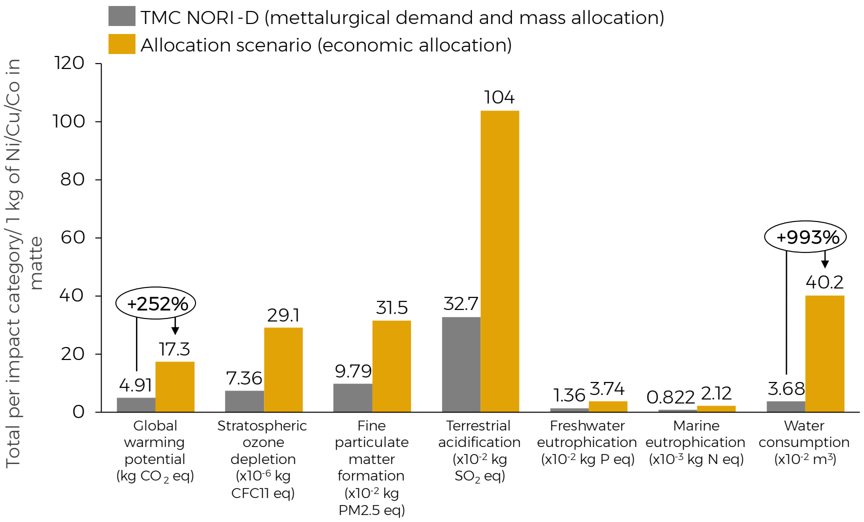
Sensitivity analysis 4) allocation within the pyrometallurgical step

There is agreement, that upstream processes such as mining and concentrating are well defined by mass allocation whereas economic allocation is deemed more appropriate for smelting and refining[1,2].

In the TMC NORI-D model, the smelting stage is part of the pyrometallurgical step in which knowledge of the metallurgical demands per product helped avoid the use of allocation. However, both manganese silicate and Ni/Cu/Co matte are produced in the pyrometallurgical process, and the metal content is known. Such metal content plays a significant part in value for its buyers.

If there wasn't economic value to the manganese silicate in slag, it would be classed as waste. Its economic value is dependent on logistical factors; for example, the proximity to buyers is key as transportation costs can surpass product value. Also, the market capacity to absorb the new supply is an important factor in determining economic value. The annual volume here estimated by TMC currently represents 6% of the world's manganese supply, according to Benchmark internal research.

The prices on the bar graph in the previous slide are adopted and the products of the system are shared as follows: Nickel 45%, Copper 16%, Cobalt 10% and Manganese silicate 29%. The effect of economic allocation in the pyrometallurgical step is presented on the right.



Emissions difference between allocation scenarios

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1. Santero and Hendry, 2016. Harmonization of LCA methodologies for the metal and mining industry. The International Journal of Life Cycle Assessment, 21(11), pp.1543-1553.
2. Nickel Institute, 2022. How to determine GHG emissions from nickel metal Class 1: A guide to calculate nickel's carbon footprint.

Discussion summary of the sensitivity analysis

The sensitivity analysis was conducted to investigate the changes from methodological choices in the total results. As expected, the changes in environmental credit, and economic allocation, have proven to be influential in the disclosed results, altering them and bringing additional understanding of the impacts' interpretations.

There are always uncertainties brought about by the methodological choices, but these are common in LCAs as stated in the limitations, slide 21. Firstly, this report is transparent of its affect in the results. Secondly, the choices are defended by ISO 14044.

Price variation did not affect the interpretation of results as the same patterns were observed. However, it is important to notice that while absolute price values will change, hierarchy between co-products impacts will not.

The sensitivity analysis findings were expected, reassuring the model correctness.

The location of onshore operations does not significantly influence the overall GWP results. This was expected due to low contributions from transshipment vessels within the mining stage. Thus, within mining, the fuel usage of the dynamic positioning and the nodules collection system in the mining vessels is more significant to the environmental burden than transportation of nodules onshore.

Recommendations for TMC

- TMC's opportunities to reduce emissions further for TMC NORI-D project lie mainly in the direct emissions from the use of bituminous coal in the pyrometallurgical stage. It is believed that biomass pellets as coal substitution[1,2] can potentially generate substantial emissions reductions in most impact categories. If a coal substitute is planned, Benchmark suggest a new LCA analysis once data is available. Since direct emissions from natural gas are another GHG hotspots, Benchmark suggests a higher reliance on lower emissions fuel source for onshore operations.

- The impacts of sulphuric acid and ammonia production are influenced by the choice of suppliers. It is recommended that TMC chooses suppliers with the same level of environmental consciousness of their own operations, and/or strategically engineer a more efficient use of these inputs.

- The direct water use in TMC's onshore operations is responsible for more than half of the water consumption impact category. TMC states that the water will be sourced from the municipality. Benchmark suggests looking at an alternative source such as recycled wastewater.

- The sensitivity analysis highlighted the uncertainties brought about by the methodological choices. The model created follows ISO standards and it is third-party verified. It is suggested that this report be made available in its entirety so the reader can understand the intricacies of the assessment.

- The endpoint impacts show how much further the impact from bituminous coal goes, which reflects in human health issues, ecosystems vulnerability and resource scarcity. Benchmark recommends strong action to mitigate the environmental impacts of the pyrometallurgical process.

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1. Wahlund B, Yan J and Westermark M., 2004. Increasing biomass utilisation in energy systems: A comparative study of CO2 reduction and cost for different bioenergy processing options. Biomass and Bioenergy, 26(6), pp. 531–544.
2. Nunes LJR, Matias JCO and Catalão JPS, 2014. A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. Renewable and Sustainable Energy Reviews, (40), pp. 153–160.

Future LCA considerations

- Once the location is defined by TMC and upstream suppliers are known, another LCA is suggested to update current results.
- After this report is made public, it is recommended that new scenarios be assessed based on new studies in the field and general public demand (e.g. a different functional unit).
- Near real time monitoring as part of an adaptive management system will improve accuracy of direct emissions both offshore and onshore. Once operations start, modelling those with actual data from operations is recommended.
- In future LCA studies, it is recommended that a sediments' composition be added to the analysis, but first SimaPro may need to develop impact categories more suitable for deep sea in order for this to be more accurately modelled.
- The ReCiPe 2016 method cannot account for the occupation and transformation of seabed in the ecosystems analysis, it only covers soil disturbance and habitat loss at the terrestrial level. A review and improvement of the LCIA method is suggested to capture those impacts.

Part 2. TMC NORI-D Model vs. Land-based Mining and Processing

Important considerations for route comparison

According to ISO 14044, the systems being compared must be equivalent. To avoid this pitfall, in our analysis the scope is defined in a way to enable comparison. As such, the routes have the same functional unit, equivalent methodological assumptions as system boundaries, data quality, allocation procedures, and overall decision rules. Any differences between the systems are identified and reported. Since the results are available to the public and comparisons are being made with other extraction routes, a critical review was necessary.

As highlighted in the sensitivity analysis, TMC's NORI-D production of manganese silicate is responsible for the majority of the pyrometallurgical emissions due to metallurgical demands. No other route is distributed in the same level of metallurgical accuracy due to data availability, however none of the land-based models yield a voluminous co-product in the intermediate stage as does the TMC NORI-D model.

The main challenge with LCAs is that the available data in the literature differs in methodological choices and the scope analysed to a large extent (e.g., unclear allocation choices, and different system boundary and functional units). Which significantly lowers the comparability of the data, presenting a challenge to companies.

The following analyses are estimations according to the best of knowledge of all parties involved. The routes chosen might not fully represent reality due to methodological choices applied to make them comparable such as extra refining stages or logistical assumptions. For example, in the HPAL routes, MSP and MHP are refined to metal whereas, in the majority of production, the intermediate is refined directly to sulphate.

Benchmark advises against a direct comparison to any of the routes here disclosed if methodological choices and processing technologies differ.

The land-based processing routes were modelled with background data (Ecoinvent) and foreground data from two experts in the nickel and cobalt industry (chemical engineers) who identified the most dominant processes based on the knowledge gained during 20+ years of experience in the industry.

All refining stages are economically allocated where more than one metal product is yielded, with the same price as TMC NORI-D model. For any credit assigned to a route, the same alternative production is chosen in routes that produce the same by-product (e.g. ammonium sulphate).

Consumable suppliers are global averages. It is assumed that electricity is solely provided by the country's mix in all other routes being assessed. Hence, the results only reflect the environmental impact when electricity is not sourced from elsewhere. However, in reality, the emissions from other routes can be lower if electricity is supplied by a renewable source. No specific renewable energy source is applied.

Due to averaged representation of each process technology, current emissions will differ from plant to plant. This implies intrinsic uncertainty of results that can over or under-estimate the real environmental impact. Underlying uncertainty is also present due to the nature of the global averaged datasets used for background processes.

Different processing technologies, locations worldwide, recovery rates and logistics are analysed in this comparison. Each route is identified in a cover slide before the graphs.

Data quality requirements are available on Appendix 7, slide 188.

Description of logistical choices

The logistics selected for the analysis are based on different specialists and market analysis of Benchmark's Forecast Team.

In the past year, China accounted for 73% and 75% of nickel and cobalt sulphates production, respectively. Nickel refining in China is set to decrease to between 50-60% by 2025[1].

Indonesia's refined nickel production is projected to grow by 48% in 2022. The country has also begun supplying nickel intermediates, mixed hydroxide precipitates (MHP), via High-pressure ammonium leaching (HPAL) process this year. Several of such projects are expect to follow in 2023 and beyond, although historical difficulties with HPAL projects in other countries do call into question how rapidly and cost efficiently Indonesia's projects can be ramped up. We expect the country to account for 40% of global refined nickel production in 2022, and this is due to increase to over 50% by 2025[1].

According to Benchmark's nickel specialists, another product from HPAL is mixed sulphite precipitate (MSP) which, with this processing technology, more likely comes from Philippines and is further processed in Japan. Logistical choices have been adapted to facilitate comparison. Ore grades were also generalised in laterite mining as it certainly differs from Indonesia to Philippines.

Russia is the biggest supplier in terms of tonnage per year of processed nickel sulphide. However, the Australian suppliers are more representative of the nickel sulphate market and they are set to overpass Russia in the near future[1].

The RLE is the world's leading producer of cobalt, accounting for roughly 71% of total mine supply in 2022. The country's capacity is set to increase in the coming years[1].

Pressure Oxidation Process (POX) and Caron (reductive roast and ammonium leaching) logistic routes are approximations of reality to the processing stages whilst preserving the system compatibility. If different end products or intermediates were considered, then the logistics applied would not have been representative. Due to the North American dominance on this type of processing technology for metal production, it is unlikely that the product would be shipped to be refined in China since Canada has the capability.

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1. Q3 2022 Forecast. Benchmark Mineral Intelligence 2022.

Overall routes selected for comparison

The table below illustrates the processing routes in this analysis and differences between processes technologies and efficiencies.

Processing technology	Ore	Ore grade	Mine to Intermediate region	Intermediate content	Refining region	Overall recovery rates	Methodology	Credit
RKEF RKEF & Pierce-Smith converters	Laterite	Nickel – 1.50% Cobalt – 0.02%	Indonesia	*Matte* Nickel – 75% Cobalt – 0.71%	China	Nickel - 84% Cobalt - 59%	The refining of matte to metal is economically allocated	Sodium sulphate (by-product)
DON Direct smelting **Conventional** Flash furnace & Pierce-Smith converters	Sulphide	Nickel – 0.60% Copper – 0.10% Cobalt – 0.02%	Australia	*Metal (100%)*	China	Nickel - 73% Copper - 73% Cobalt -74%	The refining of matte to metal is economically allocated	Sulphuric acid (by-product) Co-generation of electricity Sodium sulphate (by-product)
HPAL High Pressure Ammonium Leaching	Laterite	Nickel – 1.35%	Indonesia	*MHP* Nickel - 42% Cobalt - 6%	China	Nickel - 85% Cobalt - 63%	The refining of intermediate to metal is economically allocated	Ammonium sulphate (by-product)
		Cobalt – 0.08%	Phillipines	*MSP* Nickel - 60% Cobalt - 5%	Japan	Nickel - 87% Cobalt - 74%		
Caron Reductive roast and ammonium leaching	Laterite	Nickel - 1.45%	Cuba	*Metal (100%)*	Canada	Nickel - 84.5%	No allocation needed	None
Pox Pressure oxidation leach	Sulphide	Nickel - 3.5% Cobalt - 0.2%	Canada	*Metal (100%)*	Canada	Nickel - 86% Cobalt - 85%	Economic allocation	None
RLE Roasters, leaching and electrowinning	Mixed sulphide and oxides	Copper - 2.5-3% Cobalt - 0.3-0.4%	Democratic Republic of Congo	Copper Cathode Cobalt hydroxide	China	Copper - 90% Cobalt - 74%	Pre-refining the concentrate is economically allocated	None
TMC NORI-D RKEF and sulphur converter	Nodule	Nickel – 1.39% Copper – 1.14% Cobalt – 0.14%	Clarion-Clipperton Zone	*Matte* Nickel – 41% Copper – 31% Cobalt – 3%	Texas	Nickel – 95% Copper – 86% Cobalt – 77%	*Matte:* metallurgical demand (electricity, coal, natural gas) & mass allocation *Refining:* economic allocation MnSi (co-product)	Ammonium sulphate (by-product) Converter slag (by-product)

Matte comparison

TMC might sell the intermediate matte based on downstream user preference of metal format. It is unusual to compare intermediate products, due to their difference in content and downstream processes making part of the majority of studies. In an effort to make them comparable, the final environmental impact is disclosed in terms of the equivalent functional unit: **1 kg of metals contained in matte.**

Processing technology	Ore	Ore grade	Mine to Intermediate region	Intermediate content	Refining region	Overall recovery rates	Methodology	Credit
DON Direct smelting	Sulphide	Nickel – 0.60%	Australia	***Matte*** *Nickel – 63%*	Australia	Nickel - 73%	The refining of matte to metal is economically allocated	Sulphuric acid (by-product) Co-generation of electricity Sodium sulphate (by-product)
		Copper – 0.10%		*Copper – 11%*		Copper - 73%		
Conventional Flash furnace & Pierce-Smith converters		Cobalt – 0.02%		*Cobalt – 1%*		Cobalt -74%		
TMC NORI-D RKEF and sulphur converter	Nodule	Nickel – 1.39%	Clarion-Clipperton Zone	*Matte* Nickel – 41%	Texas	Nickel – 95%	*Matte:* metallurgical demand (electricity, coal, natural gas) & mass allocation *Refining:* economic allocation MnSi (co-product)	Converter slag (by-product)
		Copper – 1.14%		Copper – 31%		Copper – 86%		
		Cobalt – 0.14%		Cobalt – 3%		Cobalt – 77%		

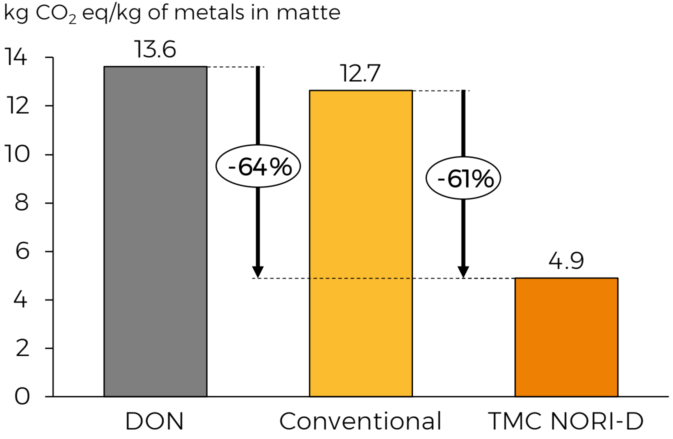
GWP – Ni/Cu/Co in Matte comparison by route

The modelled production of Ni/Cu/Co in matte of TMC's NORI-D polymetallic nodule project resulted in the lowest GWP among the three processing routes. Its projected GHG emissions are **over 60% lower** than that generated by the Conventional and DON processing routes.

The lower GHG emissions generated by TMC NORI-D matte production can be attributable to its six times **lower electricity demand**, post-distribution of energy demand between manganese silicate and matte. The GHG emissions from conventional and DON processing routes are mainly contributed by electricity demand using Australia's electricity mix while in TMC production, electricity, contributed to less than 1% of the total GWP.

TMC's NORI-D model employs **renewable electricity source** for its onshore production as opposed to Australia's carbon intense electricity mix used for DON and Conventional routes, also plays a critical role in the better performance of TMC NORI-D matte. The 0.12-1.12% **higher ore grades** of nodules also indicates greater energy savings.

Global warming potential for Ni/Cu/Co in matte by processing route



The graphs for other impact categories are presented in Appendix 8.

Overall results per midpoint impact category - Ni/Cu/Co in matte

Impact category	Unit	Conventional	DON	TMC NORI-D
Global warming	kg CO_2 eq	12.65	13.64	4.91
Stratospheric ozone depletion	kg CFC11 eq	$1.59x10^{-5}$	$1.62x10^{-5}$	$7.36x10^{-7}$
Fine particulate matter formation	kg PM2.5 eq	$1.70x10^{-2}$	$1.79x10^{-2}$	$9.79x10^{-3}$
Terrestrial acidification	kg SO_2 eq	$5.07x10^{-2}$	$5.10x10^{-2}$	$3.27x10^{-2}$
Freshwater eutrophication	kg P eq	$4.65x10^{-2}$	$4.62x10^{-2}$	$1.36x10^{-3}$
Marine eutrophication	kg N eq	$1.23x10^{-3}$	$1.21x10^{-3}$	$8.22x10^{-5}$
Water consumption	m^3	$4.05x10^{-2}$	$5.47x10^{-2}$	$3.68x10^{-3}$

Highest emissions in that category

Lowest emissions in that category

The modelled production of Ni/Cu/Co in matte from TMC NORI-D resulted in the best environmental performance in all impact categories. The emissions from TMC NORI-D production are over 90% lower than the conventional and DON processing routes in four of the seven impact categories, namely stratospheric ozone depletion, freshwater eutrophication, marine eutrophication and water consumption.

A combination of factors have contributed to a better environmental performance in TMC NORI-D production overall. Firstly, the six times lower electricity demand (post-distribution of energy demand) and employment of a renewable source of energy for onshore onsite production have shown critical in the outperformance of TMC NORI-D route where the total TMC NORI-D emissions in each impact category are lower than the emissions from electricity alone in other routes.

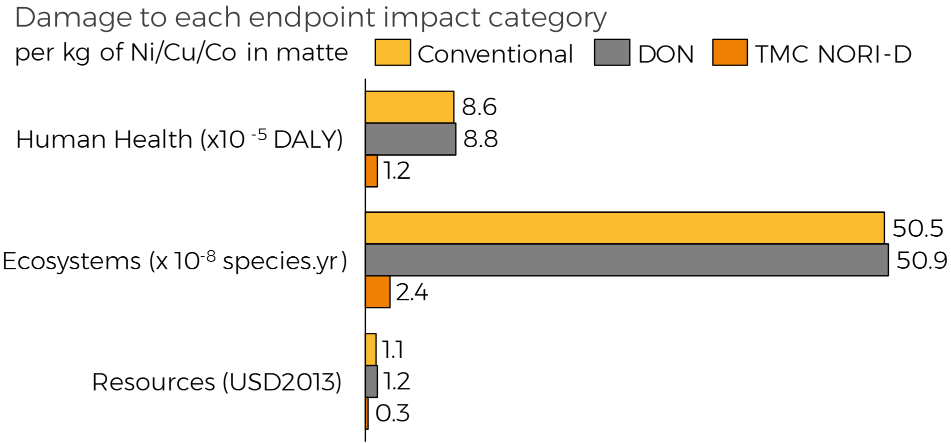
Additionally, differences in the mining process are a major contributing factor. Since nodules are unattached to the seafloor, obtaining metal ores by collecting nodules via deep-sea mining has avoided the emissions from blasting in traditional terrestrial mining, one of the chief environmental hotspots in stratospheric ozone depletion, fine particulate matter formation and terrestrial acidification in conventional and DON processing routes. Sulphidic tailings are also avoided with processing of TMC NORI-D nodules, leading to a 97% lower freshwater eutrophication emissions, proving to be the greatest distinction between the performances of TMC NORI-D and other routes.

Overall results per endpoint impact category - Ni/Cu/Co in matte

The graph below illustrates the difference between TMC NORI-D's impact as compared to the land-based routes. Damage to human health is around 8 times higher on Conventional and DON processes than for TMC NORI-D. The biggest contributor is the generation of sulphidic tailings present in both land routes and inexistent when processing TMC NORI-D nodules.

Due to limitation of the ReCiPe 2016 method, the damage to ecosystem results do not account for occupation and transformation of seabed in TMC NORI-D's model. Additionality, the data modelled for land occupation and transformation in terrestrial mining is calculated by ReCiPe with global average characterization factors. For example, it does not specifically represent Australia or the corresponding vegetation loss. Furthermore, the data does not include mine closures, meaning that comparison of damage to ecosystems is a limited representation of the reality.

TMC NORI-D also resulted in a lower impact in resource scarcity, which considers not only the metals but also fossil resources such as coal and gas. However, the analysis is not in-depth enough to suggest that deep-sea mining will or will not alleviate future environmental costs of extraction.



Nickel in Nickel Sulphate comparison

TMC might further process the intermediate matte to achieve nickel sulphate, cobalt sulphate and copper cathode. In this section, nickel routes are compared. Nickel is the primary product on all the routes presented. Ore grades and recovery rates have been averaged. In an effort to make them comparable, the final environmental impact is disclosed in terms of the equivalent functional unit: **1 kg of nickel contained in nickel sulphate.**

Processing technology	Ore	Ore grade	Mine to Intermediate region	Intermediate content	Refining region	Product	Overall recovery rates	Methodology	Credit
RKEF RKEF & Pierce-Smith converters	Laterite	Nickel – 1.50% Cobalt – 0.02%	Indonesia	*Matte* Nickel – 75% Cobalt – 0.71%	China	1 kg Nickel (100%) in NiSO4.6H20	Nickel - 84% Cobalt - 59%	The refining of matte to metal is economically allocated	Sodium sulphate (by-product)
DON Direct smelting	Sulphide	Nickel – 0.60% Copper – 0.10%	Australia	*Metal (100%)*	China		Nickel - 73% Copper - 73%	The refining of matte to metal is economically allocated	Sulphuric acid (by-product) Co-generation of electricity Sodium sulphate (by-product)
Conventional Flash furnace & Pierce-Smith converters		Cobalt – 0.02%					Cobalt -74%		
HPAL High Pressure Ammonium Leaching	Laterite	Nickel – 1.35%	Indonesia	*MHP* Nickel - 42% Cobalt - 6%	China		Nickel - 85% Cobalt - 63%	The refining of intermediate to metal is economically allocated	Ammonium sulphate (by-product)
		Cobalt – 0.08%	Phillippines	*MSP* Nickel - 60% Cobalt - 5%	Japan		Nickel - 87% Cobalt - 74%		
Caron Reductive roast and ammonium leaching	Laterite	Nickel - 1.45%	Cuba	*Metal (100%)*	Canada		Nickel - 84.5%	No allocation needed	None
Pox Pressure oxidation leach	Sulphide	Nickel - 3.5% Cobalt - 0.2%	Canada	*Metal (100%)*	Canada		Nickel - 86% Cobalt - 85%	Economic allocation	None
TMC NORI-D RKEF and sulphur converter	Nodule	Nickel – 1.39% Copper – 1.14% Cobalt – 0.14%	Clarion-Clipperton Zone	*Matte* Nickel – 41% Copper – 31% Cobalt – 3%	Texas		Nickel – 95% Copper – 86% Cobalt – 77%	*Matte:* metallurgical demand (electricity, coal, natural gas) & mass allocation *Refining:* economic allocation MnSi (co-product)	Ammonium sulphate (by-product) Converter slag (by-product)

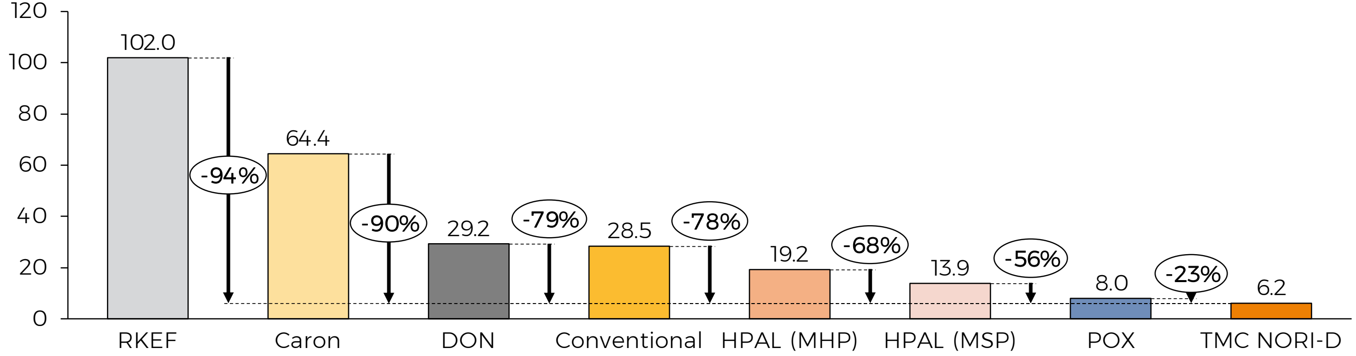
GWP – Nickel in Nickel Sulphate comparison by route

TMC NORI-D modelled production of nickel in nickel sulphate resulted in the lowest GWP. On average, TMC NORI-D model has **70% lower** GWP than the other seven production routes analysed, with the most apparent comparison being between RKEF processing route and TMC NORI-D where the latter is 94% lower. To illustrate, the electricity mix in Indonesia, powered by over 50% of fossil fuels, contributed to approximately 40% of GWP in the RKEF route. Meanwhile, for processing of TMC NORI-D nodules TMC has committed to 100% renewable electricity. As a result, TMC NORI-D electricity usage contributed to only 1% of its GWP of producing nickel in nickel sulphate (slide 41). The situation is similar with the DON and Conventional routes which use the carbon intensive Australian electricity mix[1]. **Lower electricity consumption** (post-distribution of electricity demand) and **cleaner electricity source** are the causes of the lower GWP in TMC NORI-D project when compared to the analysed terrestrial routes.

Another primary cause for the differences in values is the direct emissions from the different processes: refining process from matte to nickel metal in Caron and POX routes, and the production of intermediate MSP and MHP from laterites. Therefore, the direct emissions are a combined outcome of the use of different reagents and energy inputs in the process. An example of the major contributors in each of the two processes in the Caron and MSP/MHP routes is the use of heavy fuel oil and limestone, respectively.

Global warming potential for nickel by processing route

kg CO_2 eq/kg of nickel in nickel sulphate



The graphs for other impact categories are presented in Appendix 9.

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[1] *IEA, 2022. Energy Statistics Data Browser, IEA, Paris, link.*

Overall results per midpoint impact category - Nickel in Nickel Sulphate

Highest emissions in that category

Lowest emissions in that category

Impact category	Unit	RKEF	Conventional	DON	HPAL (MHP)	HPAL (MSP)	Caron	POX	TMC NORI-D
Global warming	kg CO_2 eq	101.96	28.47	29.21	19.23	13.87	64.43	7.97	6.17
Stratospheric ozone depletion	kg CFC11 eq	1.41x10^{-5}	2.71x10^{-5}	2.75x10^{-5}	3.10x10^{-6}	3.08x10^{-6}	1.73x10^{-5}	3.35x10^{-6}	7.33x10^{-7}
Fine particulate matter formation	kg PM2.5 eq	1.19	4.29x10^{-2}	4.31x10^{-2}	2.62x10^{-1}	1.60x10^{-1}	3.17x10^{-2}	3.95x10^{-2}	9.23x10^{-3}
Terrestrial acidification	kg SO_2 eq	9.62x10^{-1}	1.32x10^{-1}	1.29x10^{-1}	6.87x10^{-1}	5.32x10^{-1}	9.46x10^{-2}	1.25x10^{-1}	3.09x10^{-2}
Freshwater eutrophication	kg P eq	9.10x10^{-2}	7.64x10^{-2}	7.58x10^{-2}	9.12x10^{-3}	5.21x10^{-3}	9.51x10^{-3}	2.87x10^{-3}	9.84x10^{-4}
Marine eutrophication	kg N eq	5.51x10^{-3}	2.30x10^{-3}	2.26x10^{-3}	-1.78x10^{-3}	-1.25x10^{-3}	1.25x10^{-4}	1.80x10^{-4}	-2.15x10^{-3}
Water consumption	m^3	3.13x10^{-1}	1.25x10^{-1}	1.50x10^{-1}	2.50x10^{-1}	2.39x10^{-1}	1.67x10^{-1}	1.51x10^{-1}	5.46x10^{-2}

Overall, the modelled production of nickel in nickel sulphate from TMC NORI-D nodules resulted in the best environmental performance among the eight processing routes. The emissions from TMC NORI-D production are over 80% lower on average than the other routes in four out of seven impact categories, except for GWP and water consumption where the emissions are over 70% lower on average, as well as marine eutrophication. Accounting for the ammonium sulphate environmental credit towards marine eutrophication has led to an average of -532% difference, causing TMC NORI-D's production to have a net avoided emissions representing the greatest emissions savings across all impact categories.

Overall results per midpoint impact category - Nickel in Nickel Sulphate

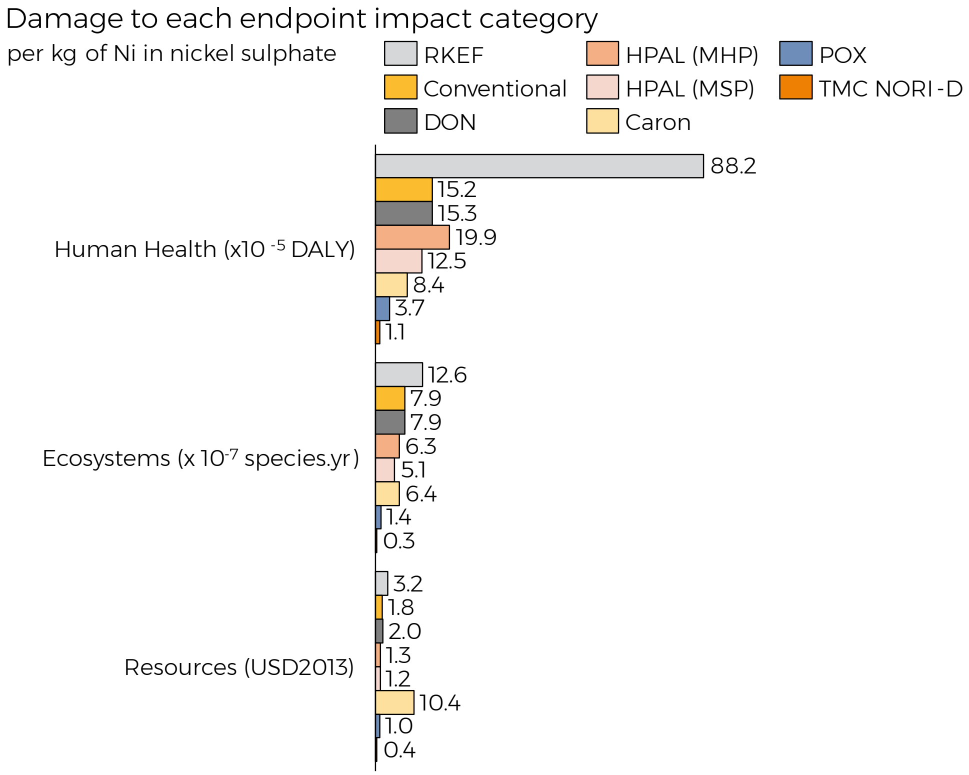
As discussed previously, the use of renewable electricity leads to a better environmental performance by the modelled TMC NORI-D production of nickel in nickel sulphate. An average of approximately 10% higher nickel recovery rates in TMC NORI-D model also helps enhance energy savings. It is interesting to note that the use of sulphuric acid in the MHP and MSP routes are respectively 5-6 times higher than in TMC NORI-D, which is the main reason for the lower TMC's emissions in most categories.

The absence of sulphidic tailings in TMC NORI-D production has proved significant in lowering the freshwater eutrophication emissions. Avoiding the use of heavy fuel oil in operating machines contributes to TMC NORI-D production outperforming the Caron process. Another critical contributor to the better performance of TMC NORI-D production include the absence of blasting in the mining stage, which are also causes behind the outperformance of TMC NORI-D over the MHP, MSP, POX and Caron routes.

Due to the purchase of oxygen from global suppliers with a high share of Asian suppliers that rely in dirtier electricity mixes, oxygen contributes to over 10% in five impact categories of the POX route (GWP, ozone depletion, freshwater and marine eutrophication and water consumption). On the other hand, TMC NORI-D production has an average of 304% lower emissions in these same categories, thanks to onsite production of oxygen using renewable energy sources which led to zero emissions from oxygen production. Although water consumption is the only exception since oxygen production consumes water, the contribution from oxygen to water consumption is still 9% lower than that of the POX route.

Although the RKEF route is similar to TMC NORI-D modelled production in terms of pyrometallurgical process for converting ore to matte, the emissions from TMC NORI-D are much lower by 83-139% in all impact categories. This difference in emissions is driven by TMC NORI-D's model which has an 11% higher nickel recovery rate, 85% lower electricity consumption rate, plus it uses renewable electricity source and has a 90% lower coal consumption.

Overall results per endpoint impact category - Nickel in Nickel Sulphate



The graph on the left illustrates that TMC NORI-D's processes are by far less damaging to the environment as compared to dominating nickel routes. The Indonesian electricity mix is heavily reliant on fossil fuels and is used on the RKEF route and contributes to 75% of damage to human health. For Conventional and DON processes impact, the sulphidic tailings are the major contributor to damage to human health. On HPAL routes, such as MHP and MSP, sulphur dioxide emissions from the use of sulphuric acid are responsible for more than 60% of health issues.

As previously stated, the ecosystem results do not account for occupation and transformation of seabed in TMC NORI-D's model. This shows the limitations of the method (ReCiPe 2016) for such analysis.

Furthermore, the data modelled for terrestrial mining is calculated with global characterization factors, which means that it does not represent a specific country or the corresponding type of vegetation loss. In addition, the data does not include mine closures, meaning that comparison of damage to ecosystems is a limited representation of the reality.

The Caron process has the highest impact on damage to resources availability because its of the dependence on heavy fuel which contributes to more than 87% to the overall resource scarcity results for this route.

Copper cathode comparison

TMC might further process the intermediate matte to achieve nickel sulphate, cobalt sulphate and copper cathode. In this section, copper routes are compared. Nickel is the primary product on the majority of the routes presented, with copper being a co-product of these productions routes. The exception is the RLE route where copper is a co-product of cobalt production. Ore grades and recovery rates have been averaged. In an effort to make them comparable, the final environmental impact is disclosed in terms of the equivalent functional unit: **1 kg of copper cathode.**

Processing technology	Ore	Ore grade	Mine to Intermediate region	Intermediate content	Refining region	Product	Overall recovery rates	Methodology	Credit
DON Direct smelting	Sulphide	Nickel – 0.60%	Australia	*Metal (100%)*	China	1 kg of Copper cathode	Nickel - 73%	The refining of matte to metal is economically allocated	Sulphuric acid (by-product) Co-generation of electricity Sodium sulphate (by-product)
		Copper – 0.10%					Copper - 73%		
Conventional Flash furnace & Pierce-Smith converters		Cobalt – 0.02%					Cobalt -74%		
RLE Roasters, leaching and electrowinning	Mixed sulphide and oxides	Copper - 2.5-3%	Democratic Republic of Congo	Copper Cathode	China		Copper - 90%	Pre-refining the concentrate is economically allocated	None
		Cobalt - 0.3-0.4%		Cobalt hydroxide			Cobalt - 74%		
TMC NORI-D RKEF and sulphur converter	Nodule	Nickel – 1.39%	Clarion-Clipperton Zone	*Matte* Nickel – 41%	Texas		Nickel - 95%	*Matte:* metallurgical demand (electricity, coal, natural gas) & mass allocation *Refining:* economic allocation MnSi (co-product)	Ammonium sulphate (by-product) Converter slag (by-product)
		Copper – 1.14%		Copper – 31%			Copper - 86%		
		Cobalt – 0.14%		Cobalt – 3%			Cobalt - 77%		

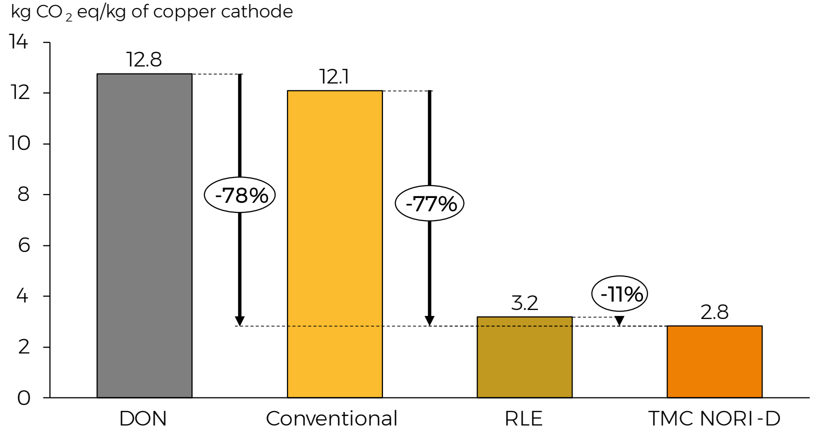
GWP – Copper cathode comparison by route

The TMC NORI-D modelled production of copper cathode resulted in **lower GWP** than all the other three processing routes analysed **by 55%** on average. For example, TMC NORI-D model has 77% lower GWP than the Conventional route, making TMC NORI-D's modelled production the route with the lowest GHG emissions to produce copper cathode between the routes here addressed.

Electricity is the main contributor for the variance in GHG emissions between Conventional, DON and TMC NORI-D routes. The total electricity consumption in the Conventional and DON routes are around 3 times higher than that of TMC NORI-D. Additionally, the electricity contributions of the Conventional and DON routes to GWP are around 234 times higher than TMC NORI-D. Hence, the lower GHG emissions of TMC NORI-D production are a result of the use of renewable electricity for onshore processing which is different for Conventional and DON use Australia's electricity mix.

On the other hand, the GHG emissions from electricity for the RLE and TMC NORI-D routes are similar. However, TMC NORI-D has a 36% higher electricity consumption. Since there is no by-product production in the RLE route, the lower GWP in TMC NORI-D is due to the environmental credit from producing the by-product, ammonium sulphate, which helps lower 48% of TMC's GHG emissions of producing copper cathode (slide 45), inducing the 11% difference between RLE and TMC production of copper cathode.

Global warming potential for copper cathode by processing route



The graphs for other impact categories are presented in Appendix 10.

Overall results per midpoint impact category - Copper cathode

Impact category	Unit	Conventional	DON	RLE	TMC NORI-D
Global warming	kg CO2 eq	12.09	12.75	3.19	2.84
Stratospheric ozone depletion	kg CFC11 eq	1.20x10^{-5}	1.22x10^{-5}	1.58x10^{-6}	3.37x10^{-7}
Fine particulate matter formation	kg PM2.5 eq	1.66x10^{-2}	1.72x10^{-2}	1.58x10^{-2}	4.24x10^{-3}
Terrestrial acidification	kg SO2 eq	5.12x10^{-2}	5.14x10^{-2}	2.65x10^{-2}	1.42x10^{-2}
Freshwater eutrophication	kg P eq	3.43x10^{-2}	3.40x10^{-2}	4.09x10^{-3}	4.53x10^{-4}
Marine eutrophication	kg N eq	1.03x10^{-3}	1.01x10^{-3}	1.02x10^{-4}	-9.87x10^{-4}
Water consumption	m3	4.43x10^{-2}	5.37x10^{-2}	3.71x10^{-2}	2.51x10^{-2}

Highest emissions in that category

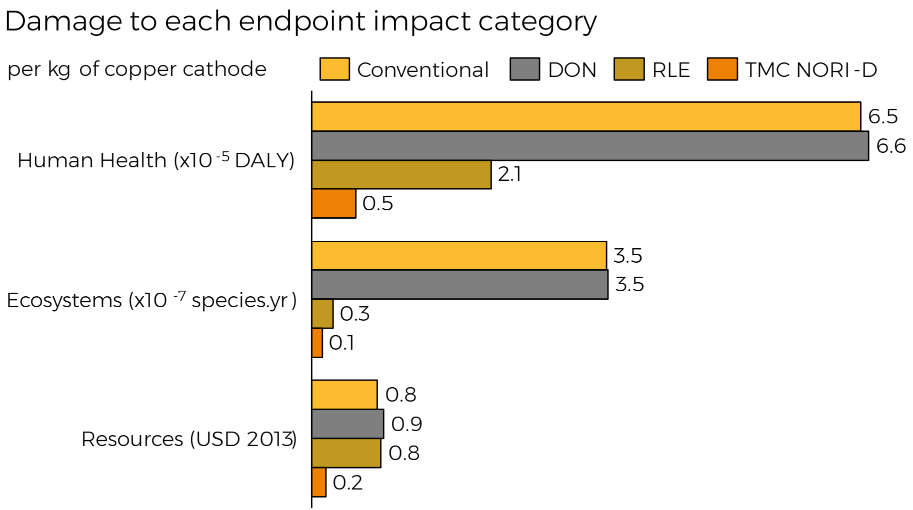
Lowest emissions in that category

Overall TMC NORI-D model resulted in the cleanest route for producing copper cathode compared to the other three routes in all seven impact categories. The emissions from TMC NORI-D production are on average more than 90% lower for ozone depletion and freshwater eutrophication. In water consumption, the TMC NORI-D route is only 43% lower on average. Nonetheless, in terms of marine eutrophication, the emissions from TMC NORI-D are 487% lower than the other routes on average. Even though environmental credits are accounted for in the conventional and DON routes, the direct burdens are too high to be offset by the avoided emissions. In contrast, the lower direct burdens of the TMC NORI-D route are offset by the higher avoided production of convertor slag (slide 45), leading to a net environmental credit in marine eutrophication.

In most cases, higher electricity demand and non-renewable energy sources were the main culprits of emissions in various categories, explaining the higher emissions in the Conventional and DON routes. On the contrary, the decisions to process nodules using renewable electricity has helped lower TMC NORI-D's emissions from electricity which contributed only 0-7% in six impact categories, thanks to an energy efficient process (considering the distribution of electricity demand) and the use of renewable electricity. Another main culprit is the emissions from blasting in Conventional and DON technologies, making TMC NORI-D perform better in ozone depletion, fine particulate matter formation and terrestrial acidification. Similar to the previous products, the absence of sulphidic tailings has helped make TMC NORI-D differ from the other routes in terms of eutrophying emissions.

The emissions difference between RLE and TMC NORI-D can be mainly explained by the environmental credit obtained by TMC NORI-D through the production of a by-product, ammonium sulphate. The RLE route does not produce by-products. And as a result, it does not receive environmental credit. Therefore, contributing to the lower emissions in TMC NORI-D in comparison.

Overall results per endpoint impact category - Copper cathode



Similar to the nickel comparison, the graph on the left illustrates that TMC NORI-D's processes are by far less damaging to the environment as compared to terrestrial copper routes.

For Conventional and DON processes, the sulphidic tailings are the major contributors to the damage to human health. As per the RLE route, the mining and beneficiation are the most impactful to human health impairment, where sulphidic tailings account for 30%, direct diesel emissions for 21% and particulate matter for 17% of the overall human health impact.

As previously stated, the damage to ecosystem endpoint results do not account for occupation and transformation of seabed in TMC NORI-D's model, showing the limitation of the method (ReCiPe 2016) for such analysis.

Furthermore, the data modelled for terrestrial mining is calculated with global characterization factors, which means that it does not represent a specific country or the corresponding type of vegetation loss. In addition, the data does not include mine closures, meaning that comparison of damage to ecosystems is a limited representation of the reality.

Interestingly, the terrestrial routes generate similar impacts to resource scarcity, with metal extraction and fossil fuel consumption contributing equally. TMC NORI-D has the lowest impact in resource scarcity between the routes analysed.

Cobalt product comparison

TMC might further process the intermediate matte to achieve nickel sulphate, cobalt sulphate and copper cathode. In this section, cobalt routes are compared. Nickel is the primary product on the majority of the routes presented, cobalt being a co-product. The exception is the RLE route where cobalt is the primary reason behind extraction. Ore grades and recovery rates have been averaged. In an effort to make them comparable, the final environmental impact is disclosed in terms of the equivalent functional unit: **1 kg of cobalt contained in final product.**

Processing technology	Ore	Ore grade	Mine to Intermediate region	Intermediate content	Refining region	Product	Overall recovery rates	Methodology	Credit
RKEF RKEF & Pierce-Smith converters	Laterite	Nickel – 1.50% Cobalt – 0.02%	Indonesia	*Matte* Nickel – 75% Cobalt – 0.71%	China	1 kg Cobalt (100%)	Nickel - 84% Cobalt - 59%	The refining of matte to metal is economically allocated	Sodium sulphate (by-product)
DON Direct smelting	Sulphide	Nickel – 0.60% Copper – 0.10%	Australia	*Metal (100%)*	China		Nickel - 73% Copper - 73%	The refining of matte to metal is economically allocated	Sulphuric acid (by-product) Co-generation of electricity
Conventional Flash furnace & Pierce-Smith converters		Cobalt – 0.02%					Cobalt -74%		Sodium sulphate (by-product)
HPAL High Pressure Ammonium Leaching	Laterite	Nickel – 1.35%	Indonesia	*MHP* Nickel - 42% Cobalt - 6%	China		Nickel - 85% Cobalt - 63%	The refining of intermediate to metal is economically allocated	Ammonium sulphate (by-product)
		Cobalt – 0.08%	Phillippines	*MSP* Nickel - 60% Cobalt - 5%	Japan		Nickel - 87% Cobalt - 74%		
Pox Pressure oxidation leach	Sulphide	Nickel - 3.5% Cobalt - 0.2%	Canada	*Metal (100%)*	Canada		Nickel - 86% Cobalt - 85%	Economic allocation	None
RLE Roasters, leaching and electrowinning	Mixed sulphide and oxides	Copper - 2.5-3% Cobalt - 0.3-0.4%	Democratic Republic of Congo	Copper Cathode Cobalt hydroxide	China	1 kg Cobalt (100%) in CoSO4.7H20	Copper - 90% Cobalt - 74%	Pre-refining the concentrate is economically allocated	None
TMC NORI-D RKEF and sulphur converter	Nodule	Nickel – 1.39% Copper – 1.14% Cobalt – 0.14%	Clarion-Clipperton Zone	*Matte* Nickel – 41% Copper – 31% Cobalt – 3%	Texas		Nickel – 95% Copper – 86% Cobalt – 77%	*Matte:* metallurgical demand (electricity, coal, natural gas) & mass *Refining:* economic allocation MnSi (co-product)	Ammonium sulphate (by-product) Converter slag (by-product)

GWP – Cobalt comparison by route

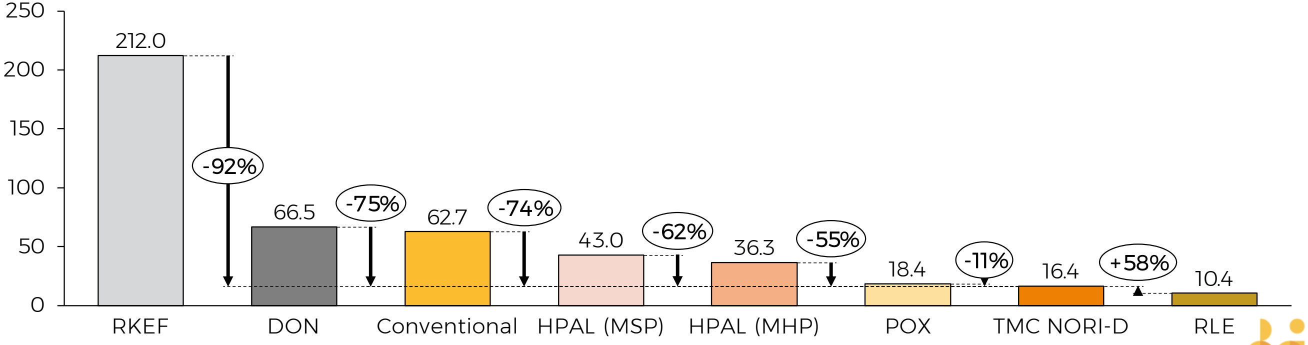
The projected GWP of TMC NORI-D production of cobalt in cobalt sulphate are lower than all the processing routes by 44% on average.

Similar to other products, approximately 40% of GHG emissions of land-based cobalt production are usually generated by both higher electricity demands and dirtier electricity mixes such as the ones in Australia (Conventional, DON) and Indonesia (RKEF)[1]. In contrast, electricity accounts for only 1% of GHG emissions of TMC NORI-D production, hence the noticeable differences in GWP between TMC NORI-D production and the aforementioned routes. Meanwhile, although the electricity consumption in the TMC NORI-D routes is 2 times higher than that of the MHP and MSP routes, the use of renewable electricity has helped TMC NORI-D lower the electricity GHG emissions by 98% and 97% as compared to the GHG emissions from the dirtier electricity mixes in Indonesia (MHP), Philippines (MSP) and China (MHP, MSP). For the MHP and MSP routes, the production of intermediates has also contributed largely to their emissions because of the use of different reagents e.g., limestone, for example.

Unlike the other products, TMC NORI-D's model has a 58% higher GWP than the RLE route placing TMC NORI-D as the second-best performing route for this category. The direct emissions from combustion of bituminous coal is the chief environmental hotspot of TMC NORI-D's cobalt production accounting for (65% of GWP) (slide 49). TMC NORI-D GHG emissions from bituminous coal are 46% higher than the GHG emissions from the top four highest contributors combined of the RLE route (pre-refining direct emissions, Chinese electricity, diesel direct emissions and quicklime indirect emissions) which account for 70% of GWP for this terrestrial route. Therefore, it is apparent that the main contributor to TMC NORI-D's GWP results is the significant amount of direct emissions from the combusting of bituminous coal, making it evident the need for lower carbon alternatives to be used to replace coal as a reductant.

Global warming potential for cobalt by processing route

kg CO_2 eq/kg of cobalt



The graphs for other impact categories are presented in Appendix 11.

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[1] IEA, 2022. Energy Statistics Data Browser, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser

Overall results per midpoint impact category - Cobalt

Highest emissions in that category

Lowest emissions in that category

Impact category	Unit	RKEF	Conventional	DON	HPAL (MHP)	HPAL (MSP)	POX	RLE	TMC NORI-D
Global warming	kg CO_2 eq	212.02	62.69	66.50	36.29	43.05	18.43	10.41	16.41
Stratospheric ozone depletion	kg CFC11 eq	2.89x10^{-5}	6.44x10^{-5}	6.56x10^{-5}	5.51x10^{-6}	9.16x10^{-6}	7.80x10^{-6}	3.51x10^{-6}	1.95x10^{-6}
Fine particulate matter formation	kg PM2.5 eq	2.50	8.89x10^{-2}	9.26x10^{-2}	5.28x10^{-1}	5.16x10^{-1}	9.09x10^{-2}	3.40x10^{-2}	2.46x10^{-2}
Terrestrial acidification	kg SO_2 eq	2.00	2.72x10^{-1}	2.74x10^{-1}	1.38	1.71	2.88x10^{-1}	8.79x10^{-2}	8.22x10^{-2}
Freshwater eutrophication	kg P eq	1.91x10^{-1}	1.83x10^{-1}	1.82x10^{-1}	1.73x10^{-2}	1.57x10^{-2}	5.49x10^{-3}	4.63x10^{-3}	2.62x10^{-3}
Marine eutrophication	kg N eq	1.16x10^{-2}	5.04x10^{-3}	4.95x10^{-3}	-3.72x10^{-3}	-3.93x10^{-3}	3.89x10^{-4}	2.04x10^{-4}	-5.71x10^{-3}
Water consumption	m^3	6.04x10^{-1}	3.16x10^{-1}	3.70x10^{-1}	4.58x10^{-1}	7.32x10^{-1}	2.78x10^{-1}	1.32x10^{-1}	1.45x10^{-1}

In the production of cobalt, TMC NORI-D model resulted in the best environmental performance in 5 out of the 7 impact categories, having an overall average of 163% lower emissions. The marine eutrophication average of -735% skews the overall average of the impact categories, and is the result of the environmental credit given to TMC NORI-D for the by-product, ammonium sulphate. Although TMC NORI-D is the second cleanest route when looking at in GWP and barely second on water consumption (10% higher), TMC NORI-D model still resulted in the best environmental performance overall when all impact categories are considered.

Overall results per midpoint impact category – Cobalt

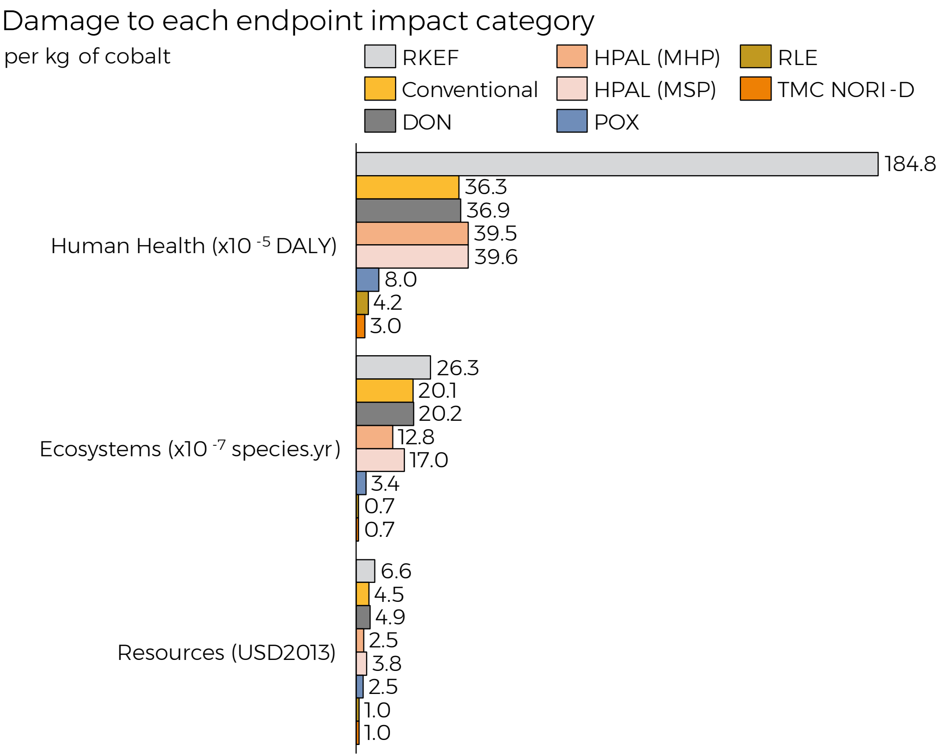
The absence of sulphidic tailings and blasting in the mining stage has helped contribute to the lower emissions of TMC NORI-D's modelled production which presents lower emissions as compared to all routes in all impact categories, except for GWP and water consumption when compared to the RLE route. Similar to all the other products discussed previously, it is observed that electricity consumption is one of the top three environmental hotspots in all impact categories within the terrestrial routes. TMC NORI-D's use of renewable electricity has played a pivotal role in the outperformance of TMC NORI-D production in the five impact categories.

Although the RKEF route is similar to TMC NORI-D production in terms of pyrometallurgical process for converting ore to matte, the emissions from TMC NORI-D are much lower, between 75-149% in all impact categories. This is because TMC NORI-D's modelled production has an 18% higher cobalt recovery rate, employs renewable electricity, thus has 81% lower electricity and 87% lower coal consumption in the TMC NORI-D's model (post-distribution in accordance with the metallurgical demand).

Similar to nickel production, in the POX route, oxygen is purchased from global suppliers with a high share of Asian suppliers that rely on fossil-fuel dominant electricity mixes. This alone contributes to 11-22% of the emissions in five out of seven impact categories for the POX route, namely GWP, ozone depletion, water consumption, freshwater and marine eutrophications. Conversely, TMC NORI-D has an average of 350% lower emissions in these categories overall, thanks to the production of oxygen onsite using renewable electricity which led to zero emissions from oxygen. Although water consumption is the only exception since oxygen production requires water, the contribution from oxygen to water consumption is still 7% lower than that of the POX route.

Other than the combustion of bituminous coal in TMC NORI-D production being the cause behind the slightly better environmental performance of RLE route in GWP, TMC NORI-D production also has an 10% higher water consumption than the RLE route. The direct water demand accounts for 67% of water consumption in TMC NORI-D (slide 185) but only 10% in the RLE route. Concurrently, the contribution of TMC NORI-D's direct water demand is 2% higher than the top three contributors to water consumption in the RLE route which accounted for 71% of RLE's water consumption. Meanwhile, the water consumption for ammonia, sulphuric acid and oxygen production in TMC NORI-D route are all higher than that of RLE's greatest water consumption contributor by 38%, 19% and 7% respectively. Since even accounting for the avoided emissions from by-production in TMC NORI-D's processes leads to higher GWP and water consumption than the RLE route which has no avoided emissions, Benchmark suggests employing recycle wastewater, optimising the use of ammonia and sulfuric acid as well as sourcing these reagents from suppliers with less emissions attached to its production and distribution.

Overall results per endpoint impact category - Cobalt



Once more, the graph on the left illustrates that TMC NORI-D's processes are by far less damaging to the environment in comparison to terrestrial cobalt routes.

Similar to the nickel comparison, the Indonesian electricity mix, on the RKEF route, contributes to 75% of damage to human health. Whilst for Conventional and DON processes impact, the sulphidic tailings are the major contributor. On HPAL routes, such as MHP and MSP, sulphur dioxide emissions are responsible for more than 60% of health issues.

As previously written, due to limitation of the ReCiPe 2016 method, the ecosystem results do not account for occupation and transformation of seabed in TMC's model.

Furthermore, the data modelled for terrestrial mining is calculated with global characterization factors, which means that it does not represent a specific country or the corresponding type of vegetation loss. In addition, the data does not include mine closures, meaning that comparison of damage to ecosystems is a limited representation of the reality.

The RKEF route has the highest impact on resource scarcity with nickel extracted, and coal, gas and crude oil use in the process chain contributing equally. TMC NORI-D has similar impact as RLE, however, TMC NORI-D biggest contributions come from natural gas and coal use, whilst for RLE is crude oil and cobalt extraction.

Conclusion: highlights

- In the study, TMC NORI-D's model performed better in each impact category analysed on all the routes chosen for comparison, except for the GWP and water consumption from TMC NORI-D's estimated cobalt sulphate production. TMC NORI-D's model still has the best environmental performance overall for cobalt production.
- To lower TMC NORI-D water consumption, Benchmark suggests utilising recycled water either from municipality sewage or industrial wastewater.
- TMC NORI-D's estimated metal recovery efficiency in matte is higher than Conventional and DON processing routes.
- TMC NORI-D's estimated nickel in nickel sulphate recovery efficiency is the highest among all processing routes.
- TMC NORI-D's estimated copper recovery is the second highest, after the RLE route.
- TMC NORI-D's estimated cobalt recovery is the second highest, after the POX route.
- Advantages of TMC NORI-D model's estimations are clear: strong co-products in terms of volume and revenue, lower electricity demand, a renewable electricity use, absence of both blasting during the mining stage and production of sulphidic tailings during processing, oxygen production on site with renewable electricity and high metal recovery rates.
- It is important to mention that the comparison are made between a conceptual project, not yet in operation, to technologies currently employed by the terrestrial mining and processing. Assumption and limitations were highlighted throughout the report.
- Some level of uncertainty is expected due to possible over-or under-estimating of the environmental impacts of the land-based processes due to use of averaged data because of variability from plant to plant, as well as use of global averaged datasets.
- Benchmark advises against a direct comparison to any of the routes here disclosed if methodological choices differ. Ore grade and recovery efficiency shall be taken into account when comparing results.

Conclusion: future considerations

- The functional unit chosen will dictate how the environmental burden is shared and later interpreted. A future project is suggested for a comparison within multi-outputs with different technologies. The “basket of products[1]” approach seems ideal to compare different sources of materials with the same finality (e.g. EV battery).
- The methodological approach chosen here made the models as close as possible to enable comparison. But, with averaged numbers from terrestrial routes versus accurate site/process data from TMC NORI-D, the results do not have the same level of accuracy. Site specific data is suggested in future comparisons or a company-to-company level of analysis for a precise conclusion.
- The impacts of land use and change were not completely assessed in this analysis. A carbon sink analysis on terrestrial mines was commissioned by TMC from Benchmark and it is a separate piece of reporting of which full results were not used in any of the LCAs presented here.
- An effort was made through endpoint analysis to assess the impact on ecosystems and some level of biodiversity analysis. However, this method is still very limited as it does not account for the ocean fauna, neither the type of vegetation and terrestrial land type.
- The benefits and possible trade-offs from TMC NORI-D’s manganese silicate (MnSi) in slag are not included in this analysis. These will be further explored in a separate piece of work with a comparison to terrestrial routes to produce Silicomanganese (SiMn).

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[1] *European Commission, 2012. Life cycle indicators basket-of-products: development of life cycle based macro-level monitoring indicators for resources, products and waste for the EU-27, link.*

Part 3. Waste Stream Analysis

Introduction: objectives

There are concerns that deep sea mining will pose threats to marine ecosystems due to disturbance of deep-sea beds. However, land mining and processing also disturb terrestrial ecosystems such as rainforest and generate hazardous waste streams which pose a threat to terrestrial ecosystems. Therefore, there is a need for conducting an analysis of the waste streams generated from the TMC process and the ones generated from land mining for the production of nickel, cobalt, and copper. This analysis will help identify the mining route that presents the least waste related impacts among the options considering the growing demand for these metals from the electric vehicle sector and the definite need of primary raw material extraction.

TMC process has two potential waste streams which are: mobilised sediments (offshore), here used as a proxy for overburden, and converter slag (onshore) if not used downstream as material for applications such as gravel for road construction. On the other hand, land ore mining, depending on the processing route, generates considerable amounts of either waste rock, tailings and slag.

Please note, waste stream analysis does not form part of the third party LCA but has been included as supplementary research to this study. The Sankey diagrams are an indicative illustration of the processes' stream because underlying assumptions for design implicates lack of precision.

Introduction: risk of soil contamination

To assess the risk of soil contamination with heavy metals, the following concentrations will be assumed for the soil from laterite ore mining (which are the typical concentrations in South Sulawesi Province, Indonesia)[1]:

Table 1. Assumed concentration of nickel in soil from laterite ore mining.

	Nickel (mg/kg)
Soil	30

The following concentrations will be assumed for the soil from sulphide ore mining (which are the typical concentrations in Johannesburg, South Africa)[2]:

Table 2. Assumed concentrations of metals in soil from sulphide ore mining.

	Nickel (mg/kg)	Copper (mg/kg)
Soil	96	66

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1. *Artiningsih, A. et al., 2019, Contamination and characteristic of Ni and Cr metal on top soil from Antang landfill, Makassar City, South Sulawesi Province, Indonesia, IOP Conference Series: Earth and Environmental Science, (235), p. 012016.*
2. Mkhize, T. (2020) *Assessment of heavy metal contamination in soils around Krugersdorp mining area, Johannesburg, South Africa., Researchspace.ukzn.ac.za.*

Introduction: risk of soil contamination

Contamination factor is then calculated with the following formula[1]:

$$CF = \frac{Cm}{Bm}$$

Where CF is the contamination factor, Cm is the mean concentration (mineral concentration in waste mg/kg), and Bm is the background concentration (laterite and sulphide ore values from previous slide).

CF between 1 and 3 indicates moderate contamination factor, considerable contamination factor from 3 to 6, and high contamination factor above 6.

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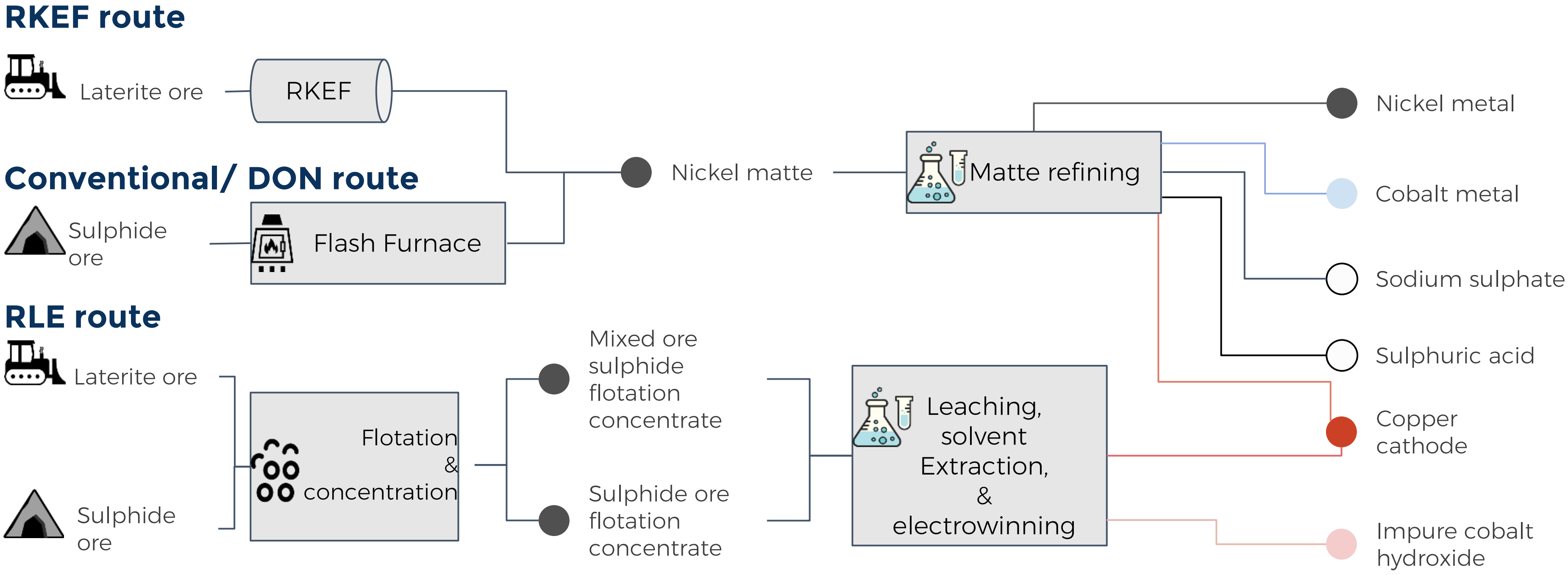
1. Jimoh, A. et al., 2020, Identification of Antioxidative Ingredients from Feverfew (Tanacetum Parthenium) Extract Substantially free of Parthenolide and other Alpha-Unsaturated Gamma-Lactones, *Open Journal of Analytical and Bioanalytical Chemistry*, 4(1), pp. 011-019.

Waste Stream analysis

Land ore processing routes considered in this analysis



RKEF route

Laterite ore

RKEF

Conventional/ DON route

Sulphide ore

Flash Furnace

Nickel matte

Matte refining

Nickel metal

Cobalt metal

Sodium sulphate

Sulphuric acid

RLE route

Laterite ore

Sulphide ore

Flotation & concentration

Mixed ore sulphide flotation concentrate

Sulphide ore flotation concentrate

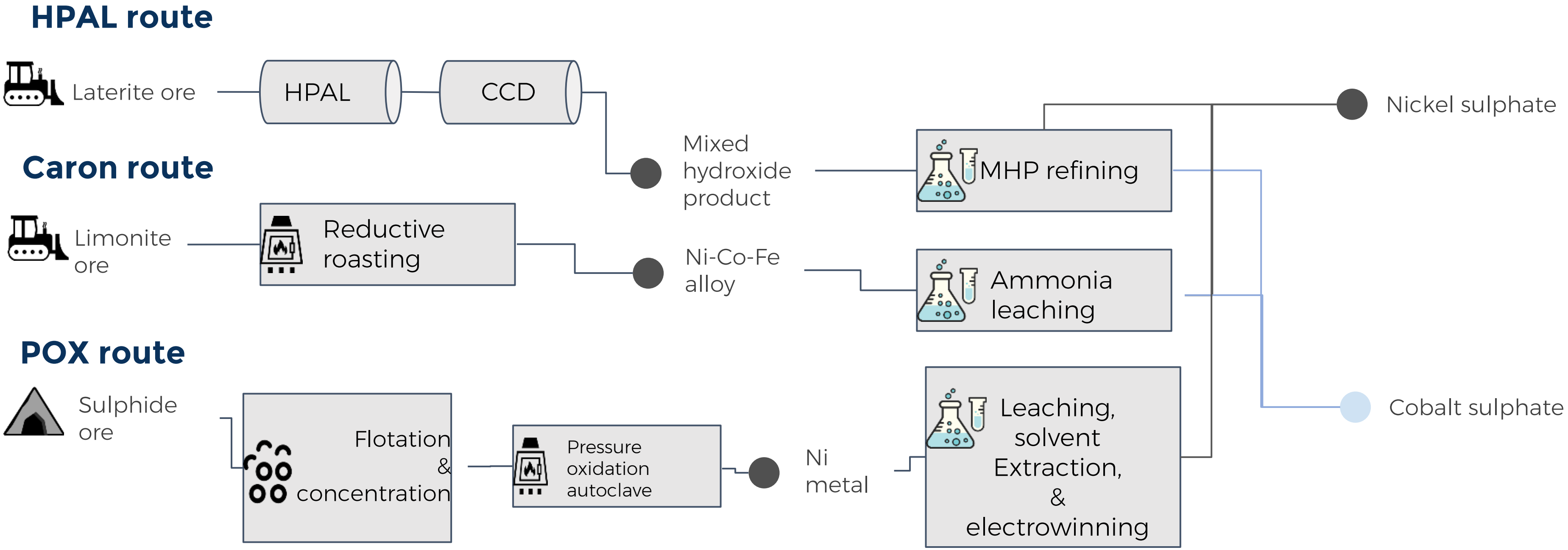
Leaching, solvent Extraction, & electrowinning

Copper cathode

Impure cobalt hydroxide

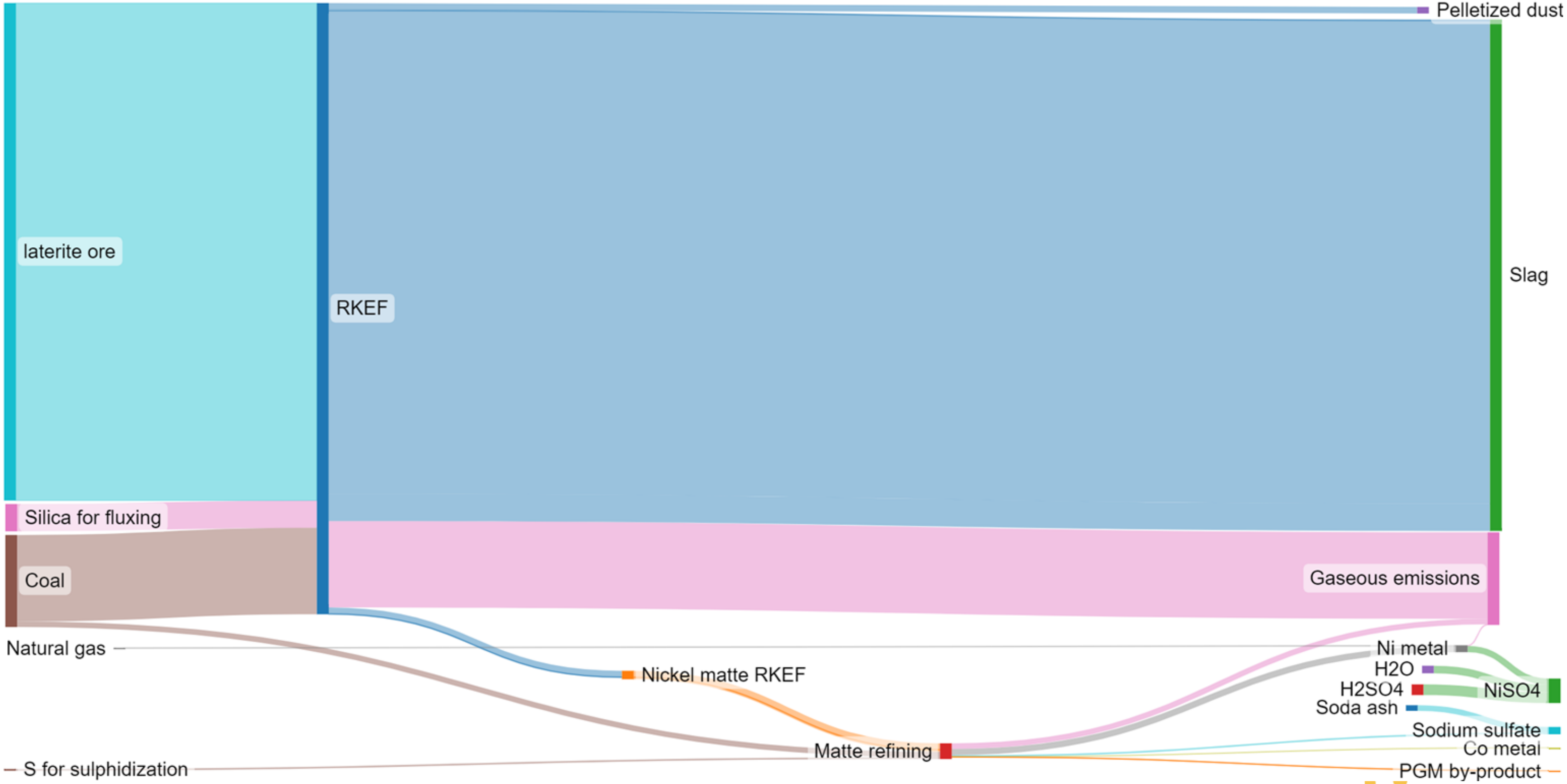
Waste Stream analysis

Land ore processing routes considered in this analysis



BENCHMARK MINERAL INTELLIGENCE

RKEF processing route: Sankey diagram



Overburden is not included in this diagram.

RKEF processing route: key assumptions

- In mining, a strip ratio of 2:1 was used to estimate the amount of mine waste (overburden rocks), this means that 2 tonnes of overburden are generated per tonne of ore mined
- The first type of waste stream from this process is the slag which is composed of the remaining laterite ore and the silica flux used for oxidising iron
- The second type of waste from this process is the stack gas which results from the coal consumed in ore drying and calcination
- A valuable by-product of the nickel matte refining process is sodium sulphate which was estimated from the contained sulphur content in the matte and soda ash used in acid neutralisation (not defined as waste)

RKEF processing route: waste stream characterisation

Table 3. Kilogram of final metal produced per kilogram of waste.

	Mine waste (kg /kg)	Mine tailings (kg/kg)	Slag (kg/kg)
Nickel	158	4	81
Cobalt	16,736	421	8,604

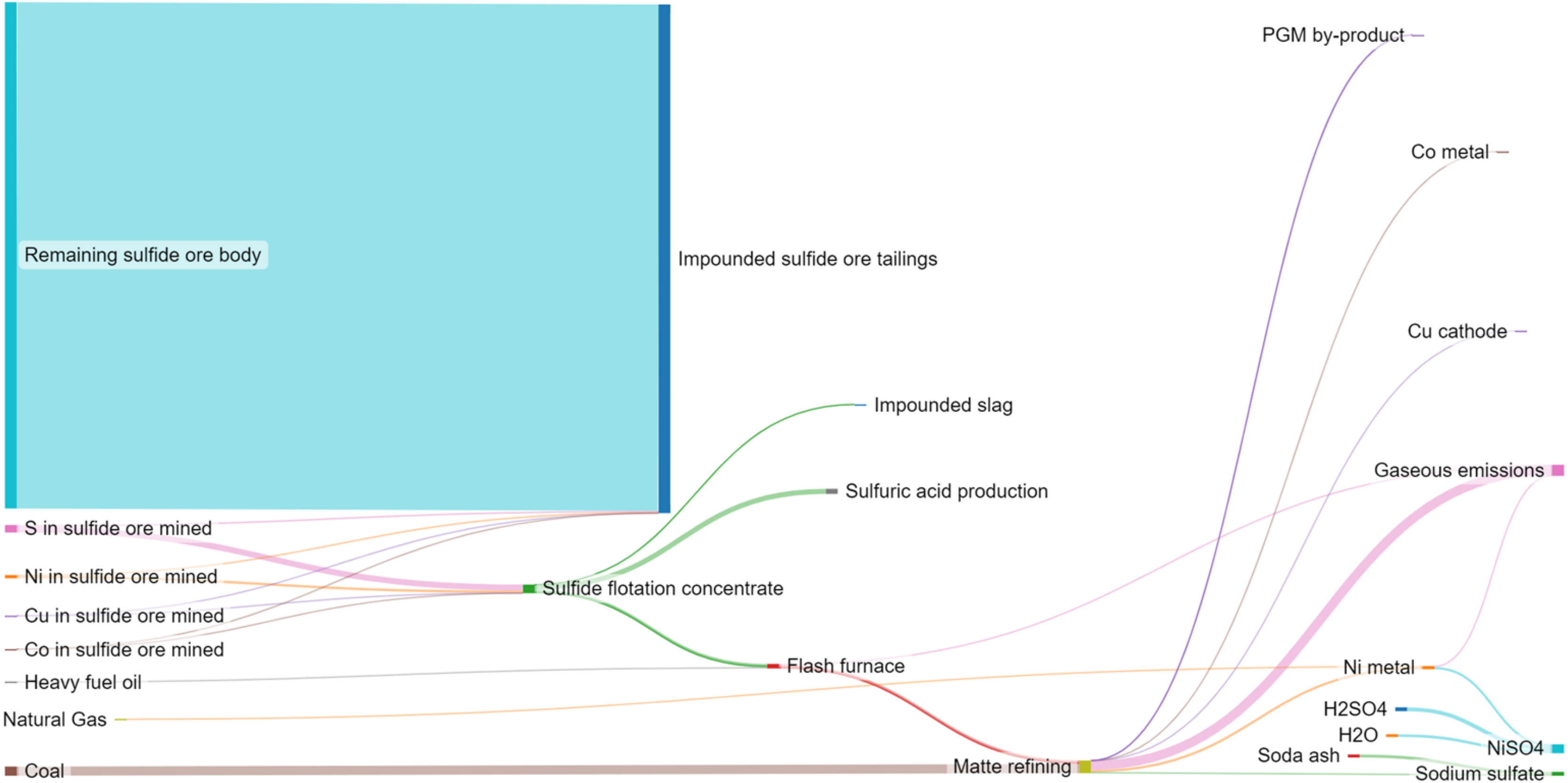
Table 4. Mineral concentration on waste stream.

	Nickel (mg/kg)	Cobalt (mg/kg)
Slag	2,200	100
	Very high contamination factor	

The analysis indicates that mine waste (overburden rocks) and mine tailings are the largest waste stream in terms of size for this process.

However, the most hazardous waste stream is the slag due to the very high concentrations of nickel and the consequent risks of soil contamination if this waste stream is landfilled.

DON/Conventional processing route: Sankey diagram



Overburden is not included in this diagram.

Conventional/DON processing route: key assumptions

- In mining, a strip ratio of 1.36:1 was used to estimate the amount of mine waste
- The first type of waste stream from this process is tailings from the flotation process that go to impoundment
- The second type of waste from this process is the slag which is composed of the remaining sulphide ore and the silica flux used for oxidising iron
- The third type of waste from this process is the stack gas which results from the coal consumed in the flash furnace
- A valuable by-product of the nickel matte refining process is sodium sulphate which was estimated from the contained sulphur content in the matte and soda ash used in acid neutralization

DON/Conventional processing route: waste stream characterisation

Table 5. Kilogram of final metal produced per kilogram of waste.

	Mine waste (kg/kg)	Mine tailings (kg/kg)	Slag (kg/kg)
Nickel	315	223	8
Cobalt	18,889	13,368	451
Copper	1,850	1,309	44

Table 6. Mineral concentration on waste stream.

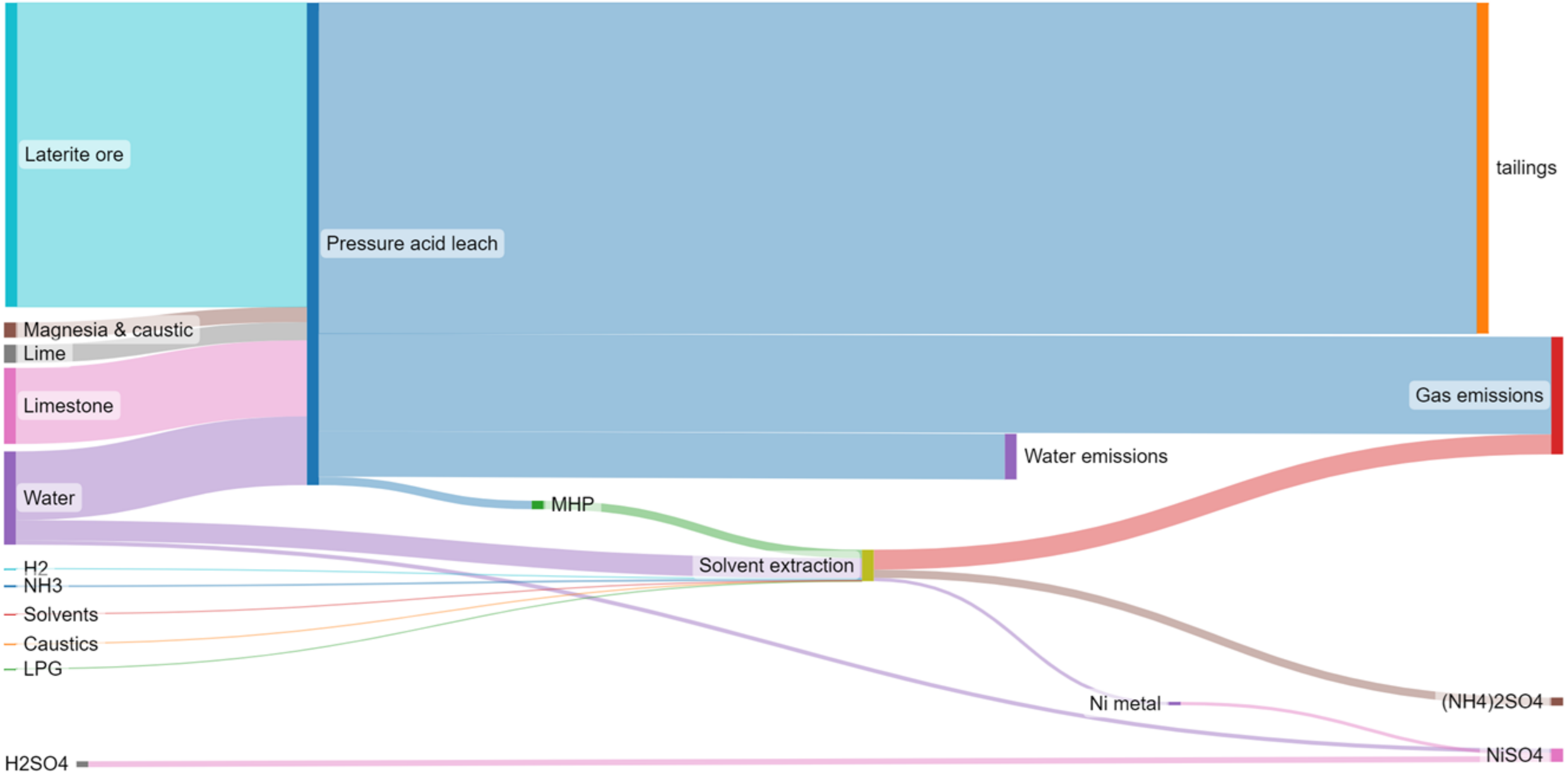
	Nickel (mg/kg)	Copper (mg/kg)	Cobalt (mg/kg)
Slag	4,200	230	70
	Very high contamination factor	Considerable contamination factor	
Mine tailings	160	300	26
	Moderate contamination factor	Considerable contamination factor	

The analysis indicates that mine waste (overburden rocks) and mine tailings are the largest waste stream in terms of size for this process.

However, the most hazardous waste stream is the slag due to the very high concentrations of nickel and the consequent risks of soil contamination if this waste stream is not valorised and landfilled.

In addition, mine tailings are the waste stream with the highest concentration of copper, which poses a considerable threat of soil contamination.

HPAL processing route: Sankey diagram



Overburden is not included in this diagram.

HPAL processing route: key assumptions

- In mining, nickel grade in ore was estimated at 1.3% and a strip ratio of 2.5:1 was assumed to estimate the amount of mine waste
- In the first stage of ore refining, the ore is leached in sulphuric acid at 250°C and 40 bars followed by counter current decantation, and the MHP will precipitate from the pregnant leach solution at pH value 7-8
- In a second step of MHP refining, MHP will go through a thickener overflow and nickel/cobalt precipitation system

Table 7. Waste stream range per input of raw material.

Waste stream	Amount
Tailings	1.06-1.15 tonnes/tonne input ore raw material
Tailings bleed	0.05-0.25 m3/tonne input ore raw material

HPAL processing route: waste stream characterisation

Table 8. Kilogram of final metal produced per kilogram of waste.

	Mine waste (kg/kg)	Mine tailings (kg/kg)	Tailings bleed (kg/kg)
Nickel	226	98	14
Cobalt	1735	755	104

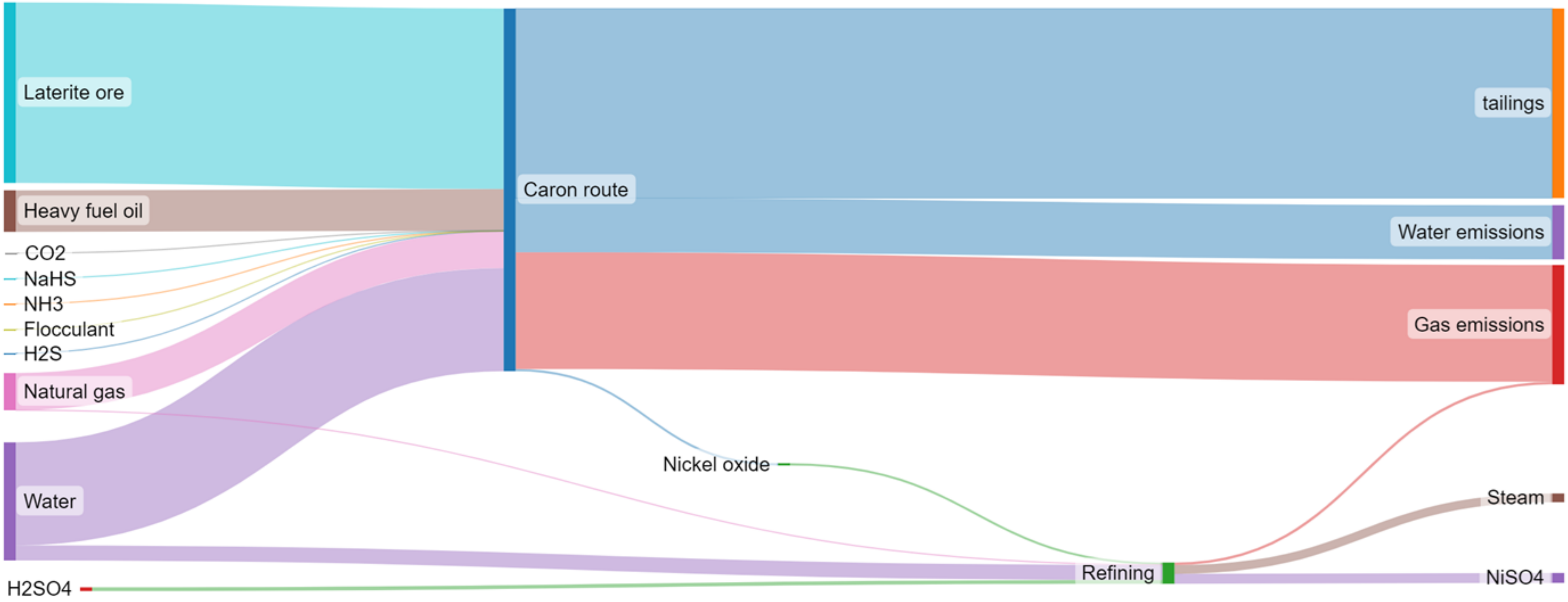
Table 9. Mineral concentration on waste stream.

	Nickel (mg/kg)	Cobalt (mg/kg)
Mine tailings	1800	110
	Very high contamination factor	

The analysis indicates that mine waste (overburden rocks) and mine tailings are the largest waste stream in terms of size for this process.

The most hazardous waste stream is the mine tailings due to the very high concentrations of nickel and the consequent risks of soil contamination. Plants close to marine environment often bleed excess tailings water into sensitive ocean ecosystems.

Caron processing route: Sankey diagram



Overburden is not included in this diagram.

Caron processing route: key assumptions

- First, the limonite ore undergoes reductive-roasting with fuel oil at 750°C. Following this process, part of the input ore is converted to a nickel-iron/nickel-cobalt iron alloy and the rest leaves the process as off-gas
- In a second step, the nickel alloy is leached in ammonia, and an appreciable part of the ore is separated from the leach liquor as tailings
- Finally, nickel in leach liquor is recovered as nickel oxide following solvent extraction and sintering

Table 10. Waste stream range per input of raw material.

Waste stream	Amount
Mine tailings	1.05-1.1 tonnes / tonne input ore raw material
Wastewater	0.1-0.5 m^3 / tonne input ore raw material
Process tailings	1.05-1.1 tonnes / tonne input ore raw material

Caron processing route: waste stream characterisation

Table 11. Kilogram of final metal produced per kilogram of waste.

	Mine waste (kg/kg)	Mine tailings (kg/kg)	Wastewater (kg/kg)	Process tailings (kg/kg)
Nickel	203	85	53	24

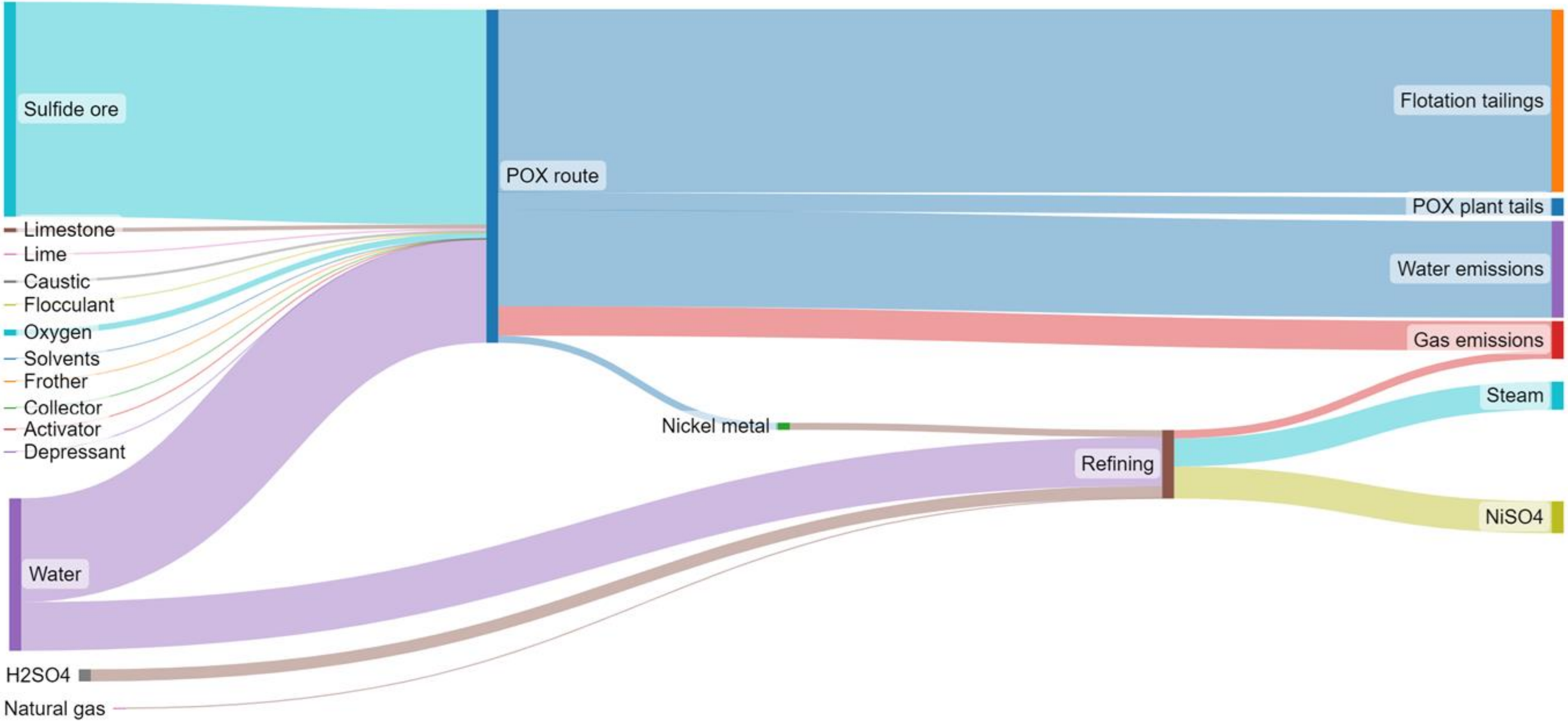
Table 12. Mineral concentration on waste stream.

	Nickel (mg/kg)	Cobalt (mg/kg)
Mine tailings	1400	76
	Very high contamination factor	

The analysis indicates that mine waste (overburden rocks) and mine tailings are the largest waste stream in terms of size for this process.

The most hazardous waste stream is the mine tailings (flotation) due to the very high concentrations of nickel and the consequent risks of soil contamination.

POX processing route: Sankey diagram



Overburden is not included in this diagram.

POX process: key assumptions

- In mining, a strip ratio of 1.36:1 was used to estimate the amount of mine waste
- The resulting flotation fraction is then directly leached in pressure oxidation autoclave which operates at similar conditions to the HPAL process

Table 13. Waste stream range per referenced material.

Waste stream	Amount
Mine tailings (flotation)	0.8-0.9 tonnes / tonne input ore raw material
Process tailings	0.4-0.7 tonnes / tonne of concentrate
Wastewater	0.4-0.5 m3 / tonne input ore raw material

POX processing route: waste stream characterisation

Table 14. Kilogram of final metal produced per kilogram of waste.

	Mine waste (kg/kg)	Mine tailings (kg/kg)	Wastewater (kg/kg)	Process tailings (kg/kg)
Nickel	41	25	13	2
Cobalt	713	446	236	43

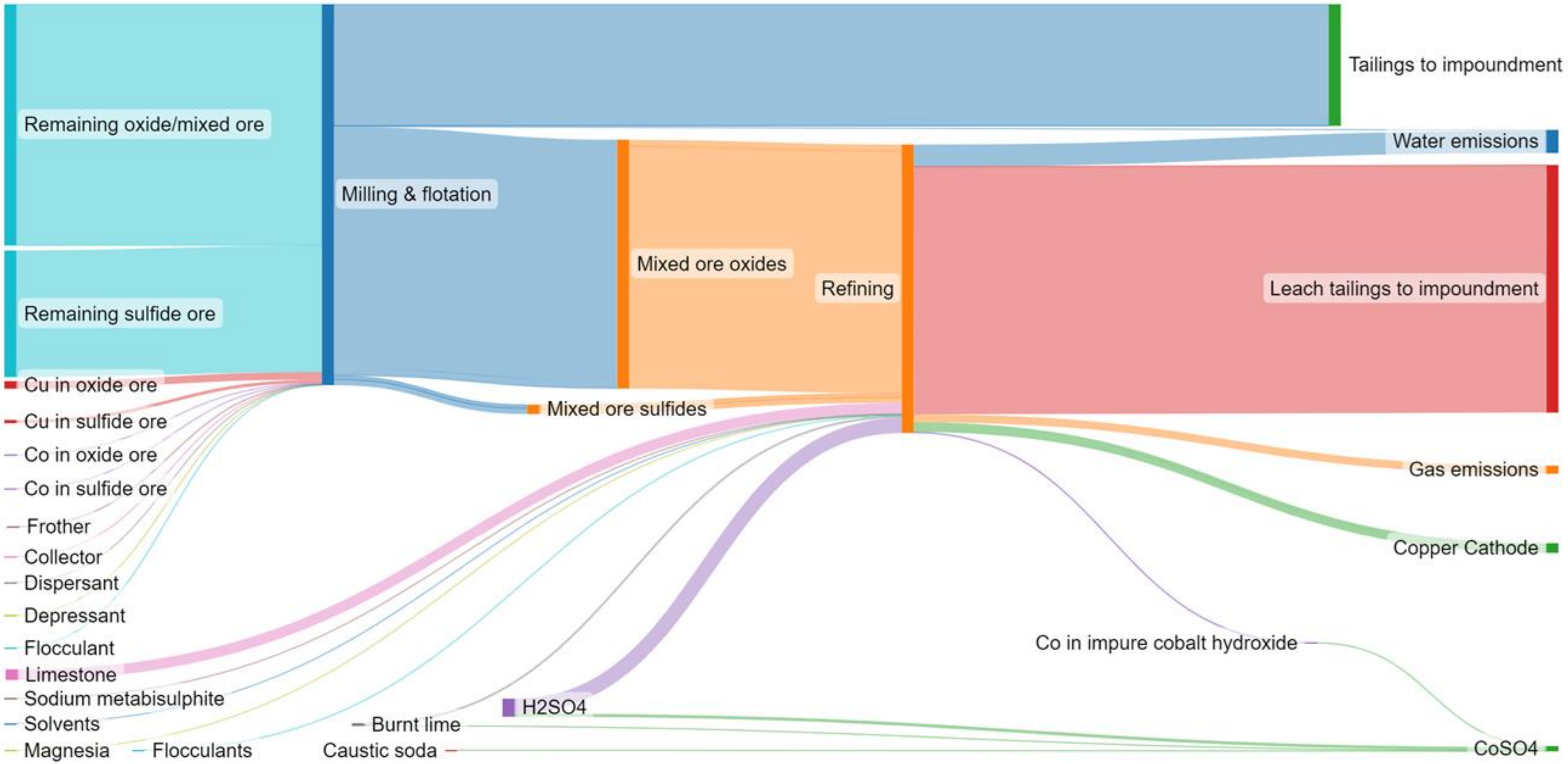
Table 15. Mineral concentration on waste stream.

	Nickel (mg/kg)	Cobalt (mg/kg)	Sulphur and Sulphides
Mine tailings	416	23.3	low levels of unoxidized sulphides
	Considerable contamination factor		
Process tailings	4,200	240	Significant quantities of elemental sulphur
	Very high contamination factor		

The analysis indicates that mine waste (overburden rocks) and mine tailings are the largest waste stream in terms of size for this process.

The most hazardous waste streams are the mine and process tailings due to the very high concentrations of nickel and cobalt and sulphur and the consequent risks of soil contamination.

RLE processing route: Sankey diagram



Overburden is not included in this diagram.

RLE processing route: key assumptions

Table 16. Key data for the RLE waste stream analysis.

	Value	Unit
Annual mixed oxide ore mined	2.59×10^6	tons / year
Annual sulphide ore mined	1.33×10^6	tons / year
Co grade in mixed oxide ore	0.3	%
Cu grade in mixed oxide ore	3	%
Co grade in sulphide ore	0.4	%
Cu grade in sulphide ore	2.5	%
Mixed oxide ore strip ratio	2:1	-
Sulphide ore strip ratio	1.36:1	-

RLE processing route: waste stream characterisation

Table 17. Kilogram of final metal produced per kilogram of waste.

	Mine waste (kg/kg)	Mine tailings (kg/kg)	Wastewater (kg/kg)	Process tailings (kg/kg)
Cobalt	690	124	2	299
Copper	70	13	-	30

Table 18. Mineral concentration on waste stream.

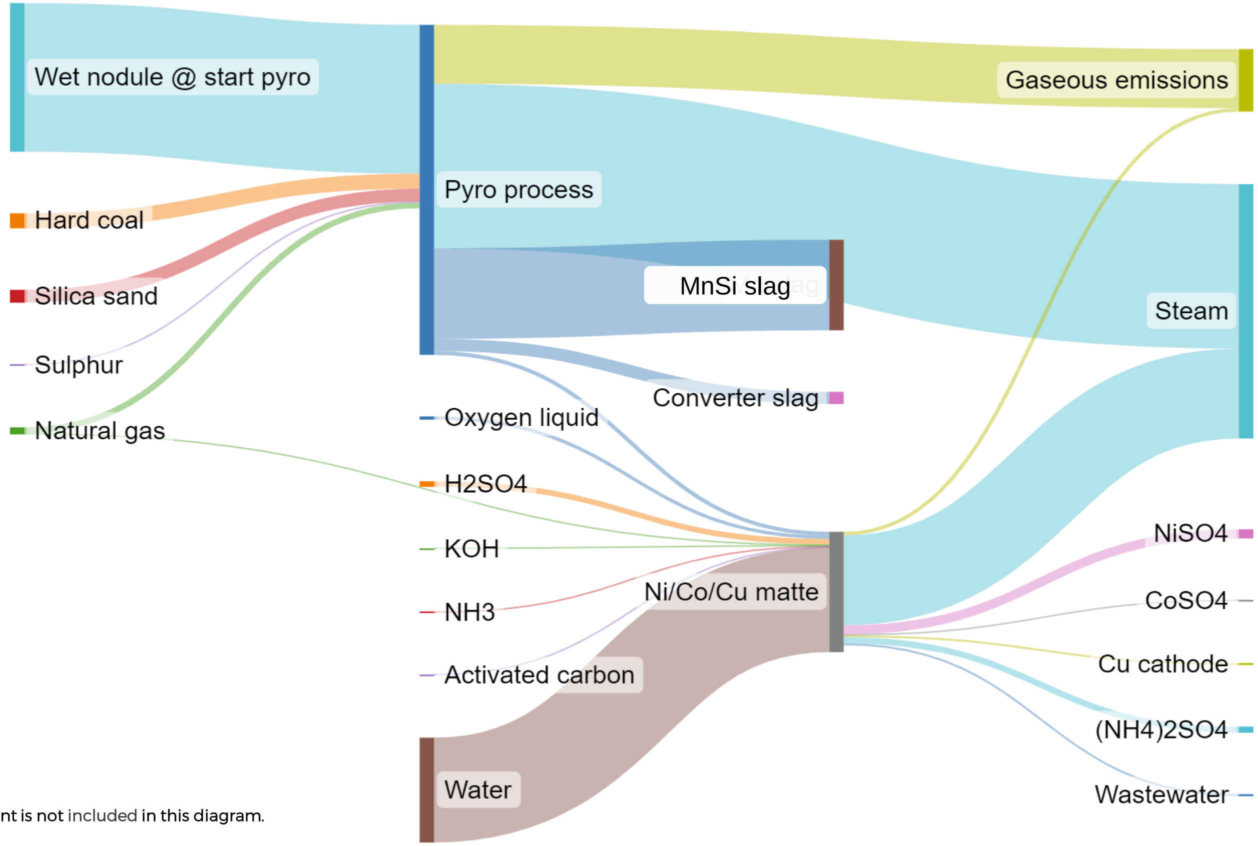
	Copper (mg/kg)	Cobalt (mg/kg)
Mine tailings	2,100	340
	Very high contamination factor	
Process tailings	3,100	900
	Very high contamination factor	

The analysis indicates that mine waste (overburden rocks) and process tailings are the largest waste stream in terms of size for this process.

The most hazardous waste stream is the process tailings (leach) due to the very high concentrations of copper and the consequent risks of soil contamination followed by mine tailings.

Furthermore, mine tailings (flotation) from sulphide ore processing are an impactful source of soil contamination due to the high content of copper and cobalt.

TMC NORI-D processing route: Sankey diagram



Mobilised sediment is not included in this diagram.

TMC NORI-D processing route: waste stream characterisation

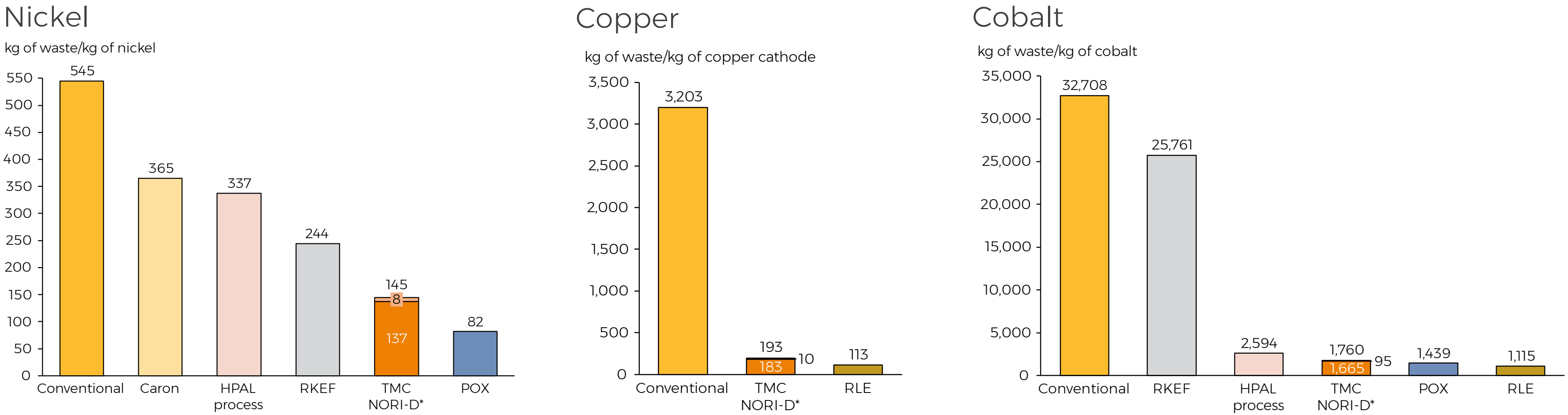
Table 19. Kilogram of final metal produced per kilogram of waste.

	Mobilised sediments (kg/kg)	Converter Slag (kg/kg)
Nickel	137	8
Cobalt	1665	95
Copper	183	10
Manganese	6	N/A

Mobilised sediments, used here as a poxy for overburden, and convertor slag, are the largest waste stream for the TMC process. The amount is comparable to, or potentially higher than some land-based routes of battery raw materials.

Converter slag is significantly lower than that from pyrometallurgical processing of laterite and sulphide ores and with a reduced content of heavy metals. Given the absence of deleterious substances, according to TMC's testing, converter slag can be used as a raw material for construction.

Mining and processing waste by processing route



*TMC: waste stream characterized by mobilised sediment, used as proxy for overburden, and converter slag, the latter will become gravel according to the client.

- Cobalt waste ratio per metal is the highest among the metals compared due to lower grades which translates into lower production volumes as compared to nickel and copper.
- TMC NORI-D's waste ratio is among the lowest mass and it mainly consists of mobilised sediment.

Conclusions

It is understood that mobilised sediments would settle on the ocean floor, and the converter slag could become gravel for road paving. Therefore, producing battery raw materials from polymetallic nodules would generate less waste than land-based mining.*

The following solid waste streams from land ores have high content of heavy metals and pose critical risks of soil contamination and wastewater streams.

1. Slag produced from the pyrometallurgical processing of sulphide ores (Conventional/DON process)
2. Mine tailings from Caron process
3. POX plant tailings (process tailings)
4. Leach tailings from copper ores mined in RLE (process tailings)

Depending on how heavy metals from land-based mining are managed, the processing of polymetric nodules may be less harmful, in terms of slag produced per unit of battery metal material and resulting heavy metals produced*.

*This assessment is based on information and data provided by TMC regarding mobilised sediments, converter slag utilisation and material content of polymetallic nodules.

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Appendices and supplementary material

Appendix 1

Methodology detailing

Methods, software and database

This LCA has used attributional aLCA over consequential cLA methods

- Both attributional (aLCA) and consequential (cLCA) methods are conducted according to ISO 14040. The main difference between the methods relate to the functional unit. While aLCA analyses the product as counted number of use, the cLCA considers the number of life cycles; for example, it includes the intrinsic consequences of recycling.
  - The scope of this LCA is defined as cradle-to-gate, and therefore it is **most appropriate to employ the attributional LCA method**, as a full life cycle (cradle-to-cradle) is not being assessed.
  - aLCA describes the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit. cLCA estimates how pollution and resource flows within a system change in response to a change in output of the functional unit.

Software and database

- This LCA was performed using SimaPro PhD Indefinite, software version 9.4.0.2 and Ecoinvent Version 3.8 (2021) database. Both are PEFCR and ISO acknowledged and preferred.

Why Ecoinvent?

- Ecoinvent provides a wide range of data, which can be used to perform different variations of environmental assessments. The database allows for studies of varying levels, provides peer-reviewed data, and is ISO and PEFCR compliant.
- Ecoinvent is widely recognised as the largest and most consistent LCI database on the market.
- Ecoinvent v.3.8 data is reported transparently.

Impact categories and impact assessment method choices

The study goal specifies that TMC requires Benchmark to perform a full LCIA. The difference between having a Life Cycle Inventory (LCI) report and a full Life Cycle Impact Assessment (LCIA) is the inclusion of ‘classification’ and ‘characterisation factors’. Including these elements is necessary to produce impact category results to give a meaningful indicator of environmental impacts of a product.

Impact categories	These group different emission factors from different substances into one effect on the natural environment.
Classification	Classification is the result of assigning substances to an impact category in which they contribute to i.e. CO_2 contributes to Global Warming Potential (GWP) and NO_2 is assigned to eutrophication, whereas chlorofluorocarbon (CFC) are assigned to both GWP and ozone depletion impact categories.
Characterisation factors	These are determined by the impact assessment methodology (e.g. ReciPe 2016). Each LCI emissions factor is multiplied by the characterisation factor before adding up the values to consider how different substances contribute differently to an impact category, such as GWP.

Impact categories and impact assessment method

Impact assessment method choice

- For this LCA, the ReCiPe 2016 impact assessment method and characterisation model have been employed in order to assign the characterisation factors to each of the LCI results. These provide the impact category indicator results and form the interpretation phase of the LCIA.
- The LCIA results in seven midpoint impact categories (slide 18) which are presented to display the critical environmental impact caused by the production of TMC's products.
- To allow for a more comprehensive understanding of the environmental impacts, the LCIA results are also presented in terms of the three endpoint categories (slide 19).
- Each midpoint and endpoint method contains factors which represent three different cultural perspectives derived from different sets of uncertainties and assumptions. The hierarchist (H) perspective is selected since it is the most common set of principles employed in scientific models respective to the plausibility of impact mechanisms and the timeframe concerned.

There are three main reasons for this choice

1. ReCiPe is one of the two most commonly employed analysis methods in the mining industry[1].
2. Due to the global nature of supply chains, ReCiPe is most appropriate as it provides a global assessment methodology.
3. These models include the most up-to-date research with regard to characterisation factors and models.

[1] *Farjana SH, Huda N and Mahmud MAP, 2019. Life cycle assessment of cobalt extraction process. Journal of Sustainable Mining, 18(3), pp. 150–161.*

The system boundary cut-off criteria

Another mandatory component within this LCA is to justify the system boundary, referred to as the 'cut-off criteria'. This explains why inputs and outputs in the model are either included or excluded, and how this relates to the overall goal of the study. 'Cut-off criteria' addresses mass, energy, and environmental relevance as appropriate.

Included in system boundary

- TMC requested a 'cradle-to-gate' analysis, therefore the life cycle phases assessed in this LCA include raw material extraction, transportation, manufacturing and processing, as shown in blue on diagram.

Raw material extraction

Upstream Transportation

Manufacturing & processing

Downstream Transportation

Usage & retail

Waste disposal treatment

Recycling

Excluded from system boundary

- The packaging information is not included. The finished product is considered as pre-packaged at the factory gate.
- As shown in grey, the transportation after packaging, usage, waste and disposal and recycle is excluded from the system boundary as this analysis is 'cradle-to-gate'.

Data requirements

1

The study goal and product system identify what data requirements are necessary and forms the basis of the LCI phase. The predominant data extraction method for this study is primary data collection. However, supplementary secondary data was used to fill data gaps where necessary. Literature reviews validated both types of data collection methods.

2

Core processing stages (process units) were identified to structure the data requirement points needed. Benchmark and TMC met weekly to collect and discuss the necessary values to fulfil the data requirement goals.

3

Site specific data is used for the offshore operations. Onshore analysis looked at three different locations in which electricity values differ in source of renewable energy and region specific data.

Data quality requirements of TMC NORI-D model

The data quality requirements are set by the study goal, and specifically, the intended target audience. This study is intended for general public release and as such a qualitative review of the dataset is complemented by a third-party revision. For completeness, the data quality has been assessed against ten data quality categories defined in ISO 14044.

Quality Categories	Details
Time related coverage	Data was either collected directly from TMC, 2022, or taken from Ecoinvent 2021 (version 3.8).
Geographical coverage	Company data: NORI-D Clarion-Clipperton Zone (CCZ), Texas (baseline model), India and Malaysia. Ecoinvent: global and rest-of-world.
Technology coverage	Technological representativeness has been defined as a present-day average. Some aspects of technology within the system process are likely to change to a new average within 5-10 years.
Precision	High. Primary data came directly from TMC and secondary data was reviewed by the company to align with their processes.
Completeness	100% of processes in the system boundary are defined and given a value.
Representatives	The dataset is reflective of TMC's offshore and onshore operations to the best of their knowledge.
Consistency	The study methodology has been applied uniformly to all components of the analysis to a high degree.
Reproducibility	High. Due to the level of detail given in this report.
Sources of the data	Reliability of the source is dependant upon the accuracy of TMC estimations, which has been tested and analysed by the company's engineers.
Uncertainty	Uncertainty of the data mostly comes from the secondary data, because of limitations on library.

LCI: offshore data input information for base model /12.47 Mtpa production

Production stage: Offshore operations

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Input from nature	Nodule content of 12.47 Mtpa wet nodules (9.47 Mtpa dry nodules)	Manganese (31%)	2940	kt	TMC	CCZ
		Nickel (1.39%)	132	kt	TMC	CCZ
		Copper (1.14%)	108	kt	TMC	CCZ
		Cobalt (0.14%)	13.3	kt	TMC	CCZ
Land transformation	Occupation, seabed, drilling and mining		738	km^{2}a	Calculated	Unspecified
	Transformation, from seabed, unspecified		1570	km^2	Calculated	Unspecified
	Transformation, to seabed, drilling and mining		1570	km^2	Calculated	Unspecified

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: offshore data input information for base model /12.47 Mtpa production

TMC model
Sensitivity models

Production stage: Offshore operations

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Offshore parts	Mining vessel, part		0.188	p	Calculated	Global
	Transport vessel, part		0.625	p	Calculated	Global
	Survey vessel, mass		378	t	Calculated	Global
	Support vessel, mass		1080	t	Calculated	Global
	Transshipment, part	Texas, USA	0.438	p	Calculated	Global
		Sarawak, Malaysia	0.500	p	Calculated	Global
		Gopalpur, India	0.563	p	Calculated	Global

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: offshore data input information for base model /12.47 Mtpa production

TMC model

Sensitivity models

Production stage: Offshore operations

Items	Input			Amount	Units	Data source	Region (on SimaPro)
Offshore fuels	Overall marine gas oils used in all vessels	Mining vessels		172	kt	TMC	Global
		Transport vessels		70.2	kt	TMC	Global
		Survey vessels		12.8	kt	TMC	Global
		Support vessels		22.8	kt	TMC	Global
		Transshipment vessels	Texas, USA	54.8	kt	TMC	Global
			Sarawak, Malaysia	108	kt	TMC	Global
			Gopalpur, India	138	kt	TMC	Global

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: offshore data input information for base model / 12.47 Mtpa production

TMC model

Sensitivity models

Production stage: Offshore operations

Items	Output			Amount	Units	Data source	Region (on SimaPro)
Output	Wet nodules collected onto system at sea			12.47	Mt	TMC	CCZ
Vessels emissions	Nitrogen oxides (NOx)	Mining vessels		2.01	kt	TMC	Unspecified
		Transport vessels		0.880	kt	TMC	Unspecified
		Survey vessels		0.134	kt	TMC	Unspecified
		Support vessels		0.260	kt	TMC	Unspecified
		Transshipment vessels	Texas, USA	0.812	kt	TMC	Unspecified
			Sarawak, Malaysia	1.50	kt	TMC	Unspecified
			Gopalpur, India	1.81	kt	TMC	Unspecified

Please note that all values in the LCI are corrected to 3 significant figures, except for the amount of wet nodules.

TMC model

Sensitivity models

LCI: offshore data input information for base model / 12.47 Mtpa production

Production stage: Offshore operations

Items	Output			Amount	Units	Data source	Region (on SimaPro)
Vessels emissions	Sulphur oxides (SOx)	Mining vessels		5.04	kt	TMC	Unspecified
		Transport vessels		2.20	kt	TMC	Unspecified
		Survey vessels		0.334	kt	TMC	Unspecified
		Support vessels		0.650	kt	TMC	Unspecified
		Transshipment vessels	Texas, USA	2.03	kt	TMC	Unspecified
			Sarawak, Malaysia	3.45	kt	TMC	Unspecified
			Gopalpur, India	3.94	kt	TMC	Unspecified

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: offshore data input information for base model / 12.47 Mtpa production

TMC model
Sensitivity models

Production stage: Offshore operations

Items	Output			Amount	Units	Data source	Region (on SimaPro)
Vessels emissions	Carbon dioxide	Mining vessels		542	kt	TMC	Unspecified
		Transport vessels		221	kt	TMC	Unspecified
		Survey vessels		40.2	kt	TMC	Unspecified
		Support vessels		71.6	kt	TMC	Unspecified
		Transshipment vessels	Texas, USA	173	kt	TMC	Unspecified
			Sarawak, Malaysia	340	kt	TMC	Unspecified
			Gopalpur, India	436	kt	TMC	Unspecified

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: offshore data input information for base model / 12.47 Mtpa production

TMC model

Sensitivity models

Production stage: Offshore operations

Items	Output			Amount	Units	Data source	Region (on SimaPro)
Vessels emissions	Wastewater	Mining vessels		664	dam^3	TMC	Unspecified
		Transport vessels		392	dam^3	TMC	Unspecified
		Survey vessels		98.0	dam^3	TMC	Unspecified
		Support vessels		235	dam^3	TMC	Unspecified
		Transshipment vessels	Texas, USA	263	dam^3	TMC	Unspecified
			Sarawak, Malaysia	407	dam^3	TMC	Unspecified
			Gopalpur, India	513	dam^3	TMC	Unspecified
Sediment emission	Mobilised Sediment			17.1	Mt	TMC	CCZ

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Mass allocation
Metallurgical demand

Production stage: Pyrometallurgical process

Items	Input			Amount	Units	Data source	Region (on SimaPro)
Intermediate resource	Wet nodule collected onto system at sea (total)			6.40	Mt	TMC	CCZ
	Wet nodule collected onto system at sea	MnSi (93%)		5.95	Mt	Calculated	CCZ
		Ni/Cu/Co (7%)		0.448	Mt	Calculated	CCZ
Fuel	Bituminous coal (total)			474	kt	TMC	Rest of the World
	Bituminous coal	Coal fraction - reduction (80%)	MnSi (62%)	235	kt	Calculated	Rest of the World
			Ni/Cu/Co (38%)	144	kt	Calculated	Rest of the World
		Fixed carbon inefficiencies - heat (20%)	MnSi (92.5%)	87.5	kt	Calculated	Rest of the World
			Ni/Cu/Co (7.5%)	7.10	kt	Calculated	Rest of the World

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model /6.4 Mtpa processing

Mass allocation
Metallurgical demand

Production stage: Pyrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Fuel	Natural gas (total)		186	kt	TMC	Global
	Natural gas	MnSi fraction (92.5%)	172	kt	Calculated	Global
		Ni/Cu/Co fraction (7.5%)	13.9	kt	Calculated	Global
Materials	Silica flux (total)		407	kt	TMC	Global
	Silica flux	Calcination - MnSi (69%)	281	kt	Calculated	Global
		Sulfidation - Ni/Cu/Co (31%)	126	kt	Calculated	Global
	Sulphur for sulfidation - Ni/Cu/Co		31.0	kt	TMC	Global
Water use	Makeup water for heat exchanges smelter (total)		5.18	hm^3	TMC	Global
	Makeup water	MnSi (93%)	4.82	hm^3	Calculated	Global
		Ni/Cu/Co (7%)	0.363	hm^3	Calculated	Global

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Mass allocation

Metallurgical demand

Production stage: Pyrometallurgical process

Items	Input				Amount	Units	Data source	Region (on SimaPro)
Electricity	Electricity for process (total)				2230	GWh	TMC	Texas
	Electricity for process	Furnace (88%)	MnSi (92.5%)		1820	GWh	Calculated	Texas
			Ni/Cu/Co (7.5%)		147	GWh	Calculated	Texas
		Non-furnace (12%)	Calcination (75%)	MnSi (92.5%)	186	GWh	Calculated	Texas
				Ni/Cu/Co (7.5%)	15.1	GWh	Calculated	Texas
			Sulfidation (25%)	Ni/Cu/Co (100%)	66.9	GWh	Calculated	Texas
	Electricity for operations vehicles (total)				9.37	GWh	TMC	Texas
	Electricity for operations vehicles	MnSi (93%)			8.71	GWh	Calculated	Texas
		Ni/Cu/Co (7%)			0.656	GWh	Calculated	Texas

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model /6.4 Mtpa processing

Mass allocation

Metallurgical demand

Production stage: Pyrometallurgical process

Items	Input			Amount	Units	Data source	Region (on SimaPro)
Heat (proxy for direct emissions)	Bituminous coal (total)			11.0	PJ	Calculated	Rest of the World
	Bituminous coal	Coal fraction (80%)	MnSi (62%)	5.48	PJ	Calculated	Rest of the World
			Ni/Cu/Co (38%)	3.36	PJ	Calculated	Rest of the World
		Fixed carbon inefficiencies (20%)	MnSi (92.5%)	2.04	PJ	Calculated	Rest of the World
			Ni/Cu/Co (7.5%)	0.166	PJ	Calculated	Rest of the World
	Natural gas (total)			9.89	PJ	Calculated	Rest of the World
	Natural gas	MnSi fraction (92.5%)		9.15	PJ	Calculated	Rest of the World
		Ni/Cu/Co fraction (7.5%)		0.742	PJ	Calculated	Rest of the World

Please note that all values in the LCI are corrected to 3 significant figures.

Mass allocation
Metallurgical demand

LCI: onshore data input information for base model / 6.4 Mtpa processing

Production stage: Pyrometallurgical process

Items	Output		Amount	Units	Data source	Region (on SimaPro)
Emissions	Steam (total)		5.18	Gt	TMC	Global
	Steam	MnSi (93%)	4.82	Gt	Calculated	Global
		Ni/Cu/Co (7%)	0.363	Gt	Calculated	Global
Avoided product	Convertor slag	Ni/Cu/Co	503	kt	TMC	Rest of the World
Pyrometallurgical products	Matte	Ni	64.2	kt	Calculated	Texas
		Cu	48.1	kt	Calculated	Texas
		Co	5.29	kt	Calculated	Texas
	Slag mass (total)		3.74	Mt	TMC	Texas
	Slag	MnSi contained in slag	1.50	Mt	Calculated	Texas

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Pyrometallurgical products	Matte (Ni/Cu/Co)	Ni (64%)	75.3	kt	Calculated	Texas
		Cu (22%)	25.9	kt	Calculated	Texas
		Co (14%)	16.5	kt	Calculated	Texas
Materials	Activated carbon, granular (total)		442	m³	TMC	Global
	Activated carbon, granular	Ni (64%)	283	m³	Calculated	Global
		Cu (22%)	97.2	m³	Calculated	Global
		Co (14%)	61.9	m³	Calculated	Global
	Ammonia, liquid (total)		48.4	kt	TMC	Rest of the World
	Ammonia, liquid	Ni (64%)	31.0	kt	Calculated	Rest of the World
		Cu (22%)	10.6	kt	Calculated	Rest of the World
		Co (14%)	6.77	kt	Calculated	Rest of the World

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Materials	Oxygen, liquid (total)		104	kt	TMC	Rest of the World
	Oxygen, liquid	Ni (64%)	66.7	kt	Calculated	Rest of the World
		Cu (22%)	22.9	kt	Calculated	Rest of the World
		Co (14%)	14.6	kt	Calculated	Rest of the World
	Potassium hydroxide (total)		1610	t	TMC	Global
	Potassium hydroxide	Ni (64%)	1030	t	Calculated	Global
		Cu (22%)	354	t	Calculated	Global
		Co (14%)	226	t	Calculated	Global

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Materials	Sulphuric acid, production (total)		176	kt	TMC	Rest of the World
	Sulphuric acid, production	Ni (64%)	113	kt	Calculated	Rest of the World
		Cu (22%)	38.8	kt	Calculated	Rest of the World
		Co (14%)	24.7	kt	Calculated	Rest of the World
Fuel	Natural gas (total)		35.6	kt	TMC	Global
	Natural gas	Ni (64%)	22.8	kt	Calculated	Global
		Cu (22%)	7.83	kt	Calculated	Global
		Co (14%)	4.98	kt	Calculated	Global

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Water use	Makeup water (total)		3300	dam^3	TMC	Global
	Makeup water	Ni (64%)	2110	dam^3	Calculated from TMC	Global
		Cu (22%)	727	dam^3	Calculated from TMC	Global
		Co (14%)	462	dam^3	Calculated from TMC	Global
Heat (proxy for direct emissions)	Natural gas (total)		1890	TJ	TMC	Rest of the World
	Natural gas	Ni (64%)	1210	TJ	Calculated from TMC	Rest of the World
		Cu (22%)	416	TJ	Calculated from TMC	Rest of the World
		Co (14%)	265	TJ	Calculated from TMC	Rest of the World

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: onshore data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Input		Amount	Units	Data source	Region (on SimaPro)
Electricity	Electricity for process (total)		266	GWh	TMC	Texas
	Electricity for process	Ni (64%)	170	GWh	Calculated from TMC	Texas
		Cu (22%)	58.6	GWh	Calculated from TMC	Texas
		Co (14%)	37.3	GWh	Calculated from TMC	Texas
	Electricity for operations vehicles (total)		3.20	GWh	TMC	Texas
	Electricity for operations vehicles	Ni (64%)	2.05	GWh	Calculated from TMC	Texas
		Cu (22%)	0.703	GWh	Calculated from TMC	Texas
		Co (14%)	0.447	GWh	Calculated from TMC	Texas

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Output		Amount	Units	Data source	Region (on SimaPro)
Emissions	Steam (total)		2830	dam^3	TMC	Rest of the World
	Steam	Ni (64%)	1810	dam^3	Calculated from TMC	Rest of the World
		Cu (22%)	623	dam^3	Calculated from TMC	Rest of the World
		Co (14%)	397	dam^3	Calculated from TMC	Rest of the World
	Wastewater to municipal utilities (total)		58.7	dam^3	TMC	Rest of the World
	Wastewater to municipal utilities	Ni (64%)	37.5	dam^3	Calculated from TMC	Rest of the World
		Cu (22%)	12.9	dam^3	Calculated from TMC	Rest of the World
		Co (14%)	8.21	dam^3	Calculated from TMC	Rest of the World

Please note that all values in the LCI are corrected to 3 significant figures.

LCI: data input information for base model / 6.4 Mtpa processing

Economic allocation

Production stage: Hydrometallurgical process

Items	Output		Amount	Units	Data source	Region (on SimaPro)
Avoided product	Ammonium sulphate (total)		192	kt	TMC	Rest of the World
	Ammonium sulphate	Ni (64%)	123	kt	Calculated	Rest of the World
		Cu (22%)	42.2	kt	Calculated	Rest of the World
		Co (14%)	26.9	kt	Calculated	Rest of the World
Hydrometallurgical products	Ni in nickel sulphate		64.2	kt	TMC	Texas
	Cu cathode		48.0	kt	TMC	Texas
	Co in cobalt sulphate		5.27	kt	TMC	Texas

Please note that all values in the LCI are corrected to 3 significant figures.

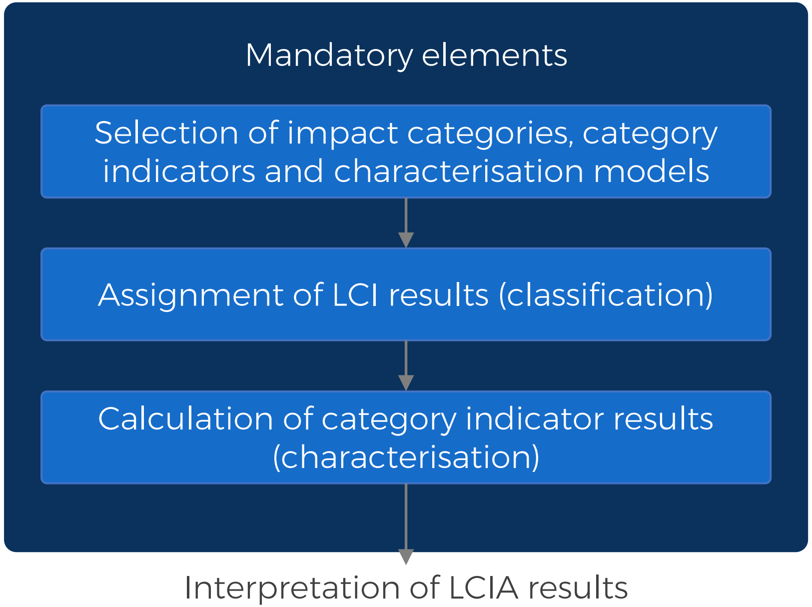
Life Cycle Impact Assessment (LCIA): overview and contents

Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) is an iterative process, whereby the study goal and scope of the LCA are continuously reviewed and considered to determine whether or not the objectives of the study have been met. It was necessary to modify the goal and scope if the assessment reflected that certain processes were not achievable. For example, in this LCA the sediments had to be treated as overburden and the vessels' parts were replaced by proxies in order to fulfil a new study goal and complete the LCA.

Choice and evaluation of impact categories can introduce subjectivity in this phase of the LCA, therefore a justification for choices have been provided.

Life Cycle Impact Assessment contents



Mandatory elements

Selection of impact categories, category indicators and characterisation models

Assignment of LCI results (classification)

Calculation of category indicator results (characterisation)

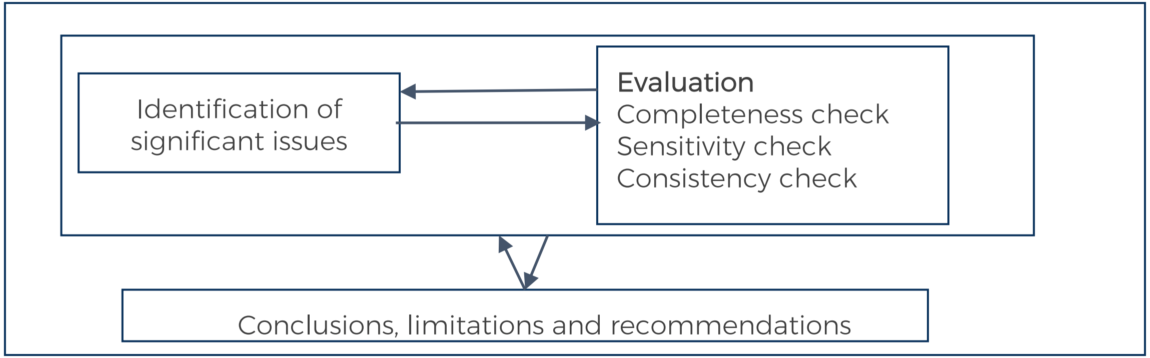
Interpretation of LCIA results

Interpretation: overview

Interpretation

The interpretation is the final phase of a LCA, and it integrates the LCI and LCIA to display the results and develop conclusions and recommendations as per the objectives of the study goal and scope. The process is again iterative and the study goal and scope, along with data collection methods, are continually reviewed. This phase is where the whole LCA study is scrutinised for its quality and its capability to fulfil the questions set in the study goal and the scope phase.

It is important to note here in the LCIA interpretation, that a LCA is a relative approach, which only gives **indicators to environmental impacts and effects and does not predict actual impacts to the environment and human health.** Transparency in the interpretation phase is of utmost importance. No results here have been doctored or edited in a way that would be deemed biased and unscientific. Additional, sensitivity analyses has been included to check and disclose model robustness and account for uncertainties.



Identification of significant issues

Evaluation
Completeness check
Sensitivity check
Consistency check

Conclusions, limitations and recommendations

Table of all ReCiPe 2016 impact categories

Impact Category	Unit	Description
Carbon footprint	kg CO_2 eq	Includes all greenhouse gases in CO_2 equivalent (CO_2 -eq) and covers scope 1, 2, and 3 emissions
Global warming	kg CO_2 eq	Emissions included: carbon dioxide, carbon monoxide, methane, nitrous oxide, chlorofluorocarbons and hydrochlorofluorocarbons
Stratospheric ozone depletion	kg CFC11 eq	Chemicals that cause the depletion of the ozone layer have chlorine or bromine groups in their molecules that interact with ozone (mainly) in the stratosphere. Ultimately they cause human health issues because of the resultant increase in UVB-radiation
Ionizing radiation	kBq Co-60 eq	Radionuclide emissions are generated in the nuclear fuel cycle (mining, processing and waste disposal) as well as during human activities, such as the burning of coal and the extraction of phosphate rock. Exposure to ionizing radiation can lead to mutations of DNA-molecules
Ozone formation, Human health	kg NOx eq	This is a result of photochemical reactions of Nitrous Oxides (NOx) and Non Methane Volatile Organic Compounds (NMVOCS). This is a health hazard to humans as it can lead to respiratory problems such as inflammation of airways and damaged lungs
Fine particulate matter formation	kg PM2.5 eq	Represents a complex mixture of organic and inorganic substances. PM2.5 can cause human health problems as it can deposit to the upper part of the airways and lungs when inhaled. Secondary PM2.5 aerosols are formed in air from emissions of sulphur dioxide (SO_2), ammonia (NH3), and nitrogen oxides (NOx), among other elements
Ozone formation, Terrestrial ecosystems	kg NOx eq	Ozone can have a negative impact on vegetation, including stunt growth and a decrease in seed production, as well as an acceleration of leaf senescence and a reduced ability to withstand stressors
Terrestrial acidification	kg SO_2 eq	Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in the acidity of the soil. Major acidifying emissions include NOx, NH3, or SO_2. This can cause extinction of species leading to damage to the terrestrial ecosystem
Freshwater eutrophication	kg P eq	Occurs due to the discharge of nutrients into soil or into freshwater bodies and hence in the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen
Marine eutrophication	kg N eq	Occurs due to the discharge of nutrients into marine environments and hence in the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen.
Terrestrial ecotoxicity	kg 1,4-DCB	Includes 1,4-Dichlorobenzene and nickel emissions to urban air, freshwater, seawater and industrial soil. Determines the damage to the ecosystem, including animals, water and the ground (soil)
Freshwater ecotoxicity	kg 1,4-DCB	Includes 1,4-Dichlorobenzene emissions (urban air, freshwater, seawater and industrial soil) and Nickel emissions (urban air, freshwater, seawater and industrial soil)
Marine ecotoxicity	kg 1,4-DCB	Consequence of the addition of essential metals to oceans, leading to toxic effects. Such essential metals are Zinc, Manganese, Molybdenum, Cobalt and Copper
Human carcinogenic toxicity	kg 1,4-DCB	Includes 1,4-Dichlorobenzene and nickel emissions to urban air, freshwater, seawater and industrial soil. Regards the damage to human health, as a result on chemicals and processes that are not known to cause cancer
Human non-carcinogenic toxicity	kg 1,4-DCB	Includes 1,4-Dichlorobenzene and nickel emissions to urban air, freshwater, seawater and industrial soil. Regards the damage to human health, as a result on chemicals and processes that are known to cause cancer
Land use	m2a crop eq	Refers to the change of land cover or land use intensification which leads to soil disturbance and loss of habitat
Mineral resource scarcity	kg Cu eq	Regards to the scarcity of various minerals such as aluminium, iron ore, silver, platinum, copper, between others. It considers the overall decrease in ore grade, the increase in ore production, thus future production and reserves
Fossil resource scarcity	kg oil eq	Regards to the scarcity of the five main fossil fuels: peat, hard coal, brown coal, crude oil and natural gas
Water consumption	m3	Attributed to the availability reduction of freshwater which leads to impacts on human health and ecosystem quality

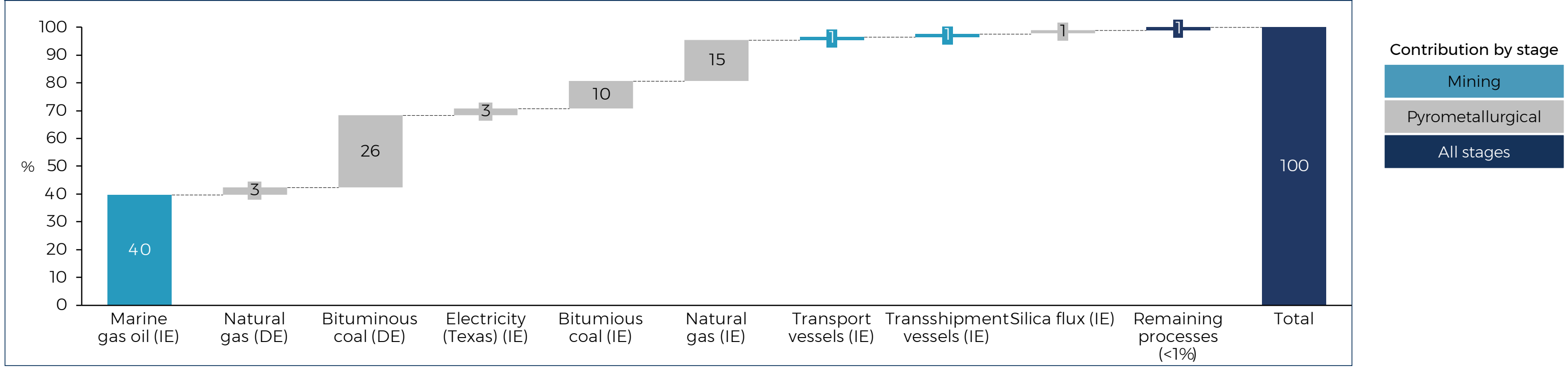
Appendix 2

Life Cycle Impact Assessment

a) Manganese silicate slag – TMC NORI-D results

Input contributions for Ozone Depletion – MnSi in slag

Total contribution per input (in %)



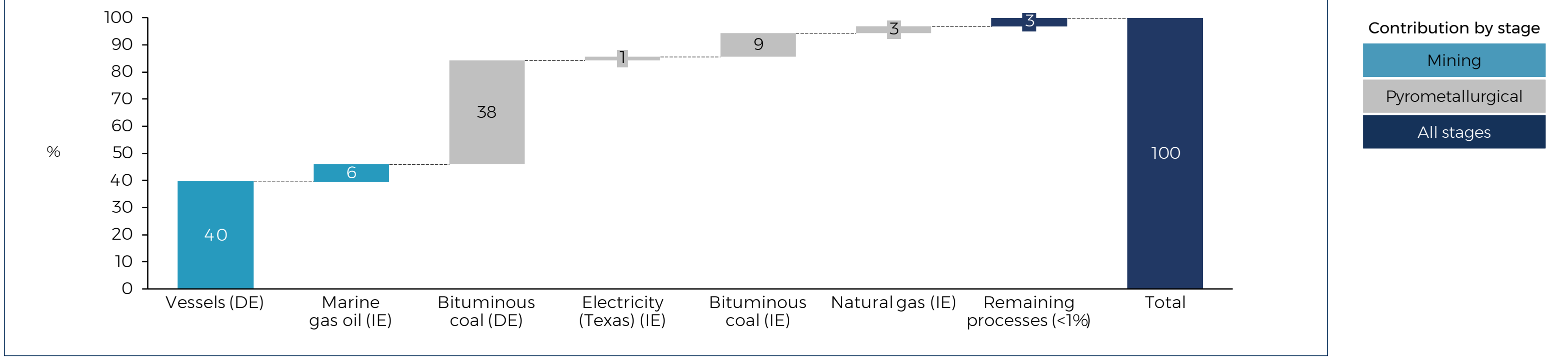
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)	Terrestrial Acidification (x10^{-5} kg SO_2 eq)	Freshwater Eutrophication (x10^{-6} kg P eq)	Marine Eutrophication (x10^{-7} kg N eq)	Water Consumption (x10^{-5} m^3)
Vessels (DE)	0.334	*	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Fine Particulate Matter Formation – MnSi in slag

Total contribution per input (in %)



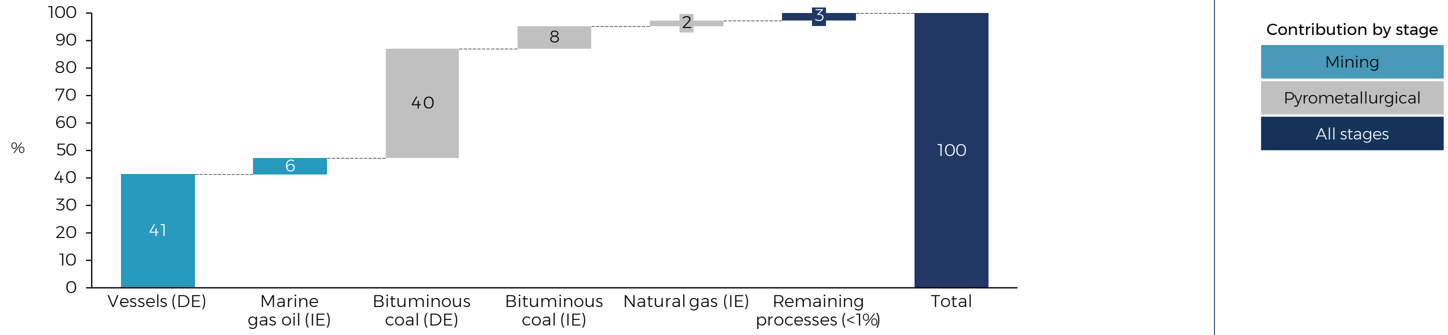
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	**Ozone Depletion (x10^{-9} kg CFC11 eq)**	**Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)**	**Terrestrial Acidification (x10^{-5} kg SO_2 eq)**	**Freshwater Eutrophication (x10^{-6} kg P eq)**	**Marine Eutrophication (x10^{-7} kg N eq)**	**Water Consumption (x10^{-5} m^3)**
Vessels (DE)	0.334	*	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Terrestrial Acidification – MnSi in slag

Total contribution per input (in %)



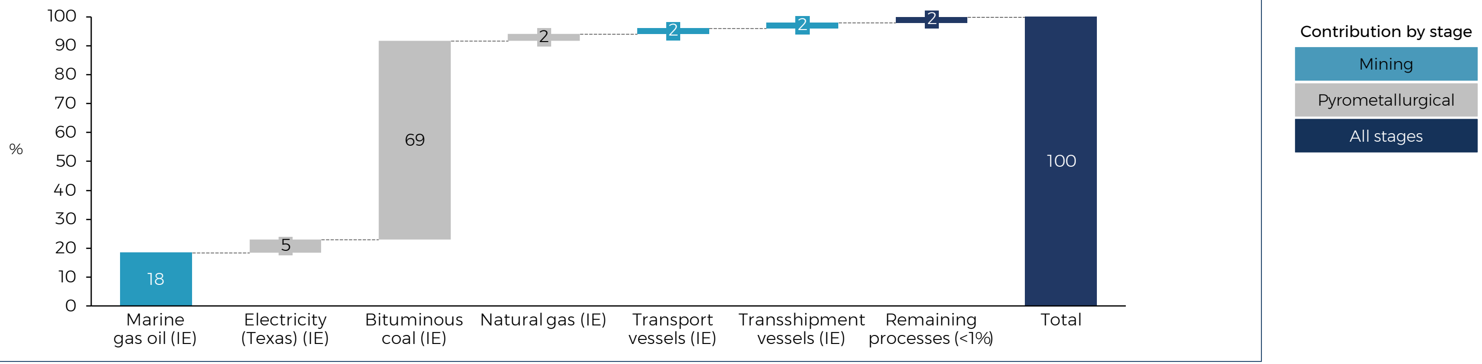
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	**Ozone Depletion (x10^{-9} kg CFC11 eq)**	**Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)**	**Terrestrial Acidification (x10^{-5} kg SO_2 eq)**	**Freshwater Eutrophication (x10^{-6} kg P eq)**	**Marine Eutrophication (x10^{-7} kg N eq)**	**Water Consumption (x10^{-5} m^3)**
Vessels (DE)	0.334	*	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Freshwater Eutrophication – MnSi in slag

Total contribution per input (in %)



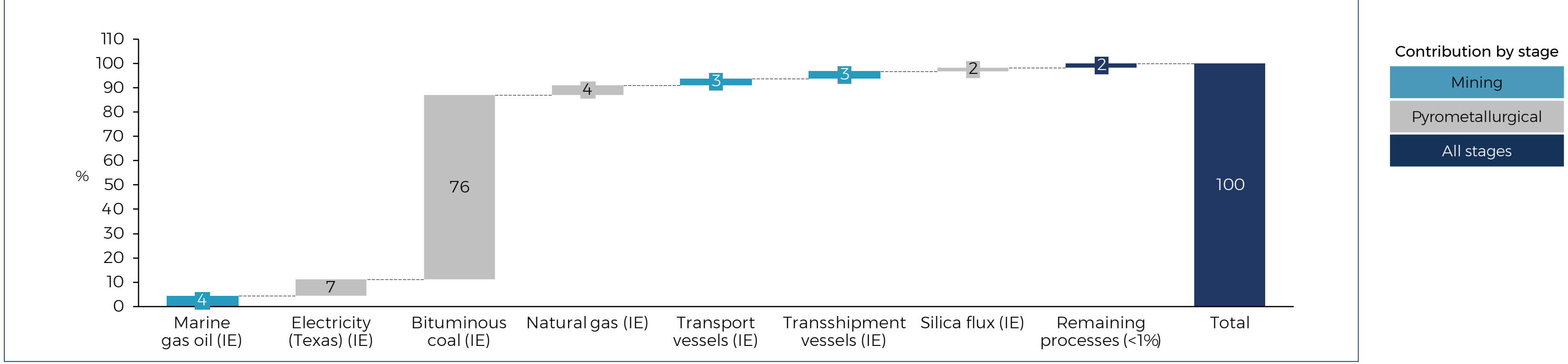
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)	Terrestrial Acidification (x10^{-5} kg SO_2 eq)	Freshwater Eutrophication (x10^{-6} kg P eq)	Marine Eutrophication (x10^{-7} kg N eq)	Water Consumption (x10^{-5} m^3)
Vessels (DE)	0.334	*	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Marine Eutrophication – MnSi in slag

Total contribution per input (in %)



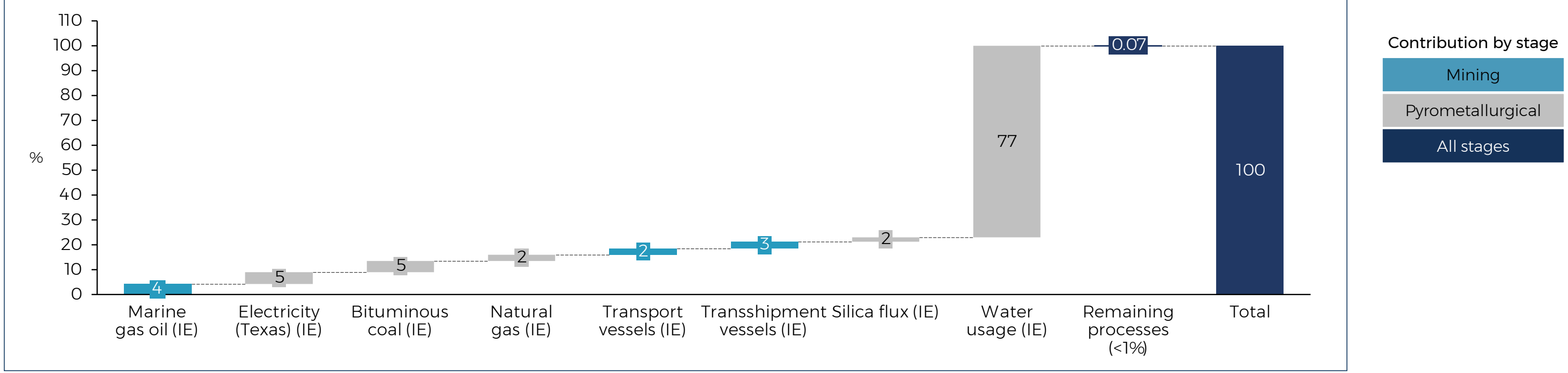
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	**Ozone Depletion (x10^{-9} kg CFC11 eq)**	**Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)**	**Terrestrial Acidification (x10^{-5} kg SO_2 eq)**	**Freshwater Eutrophication (x10^{-6} kg P eq)**	**Marine Eutrophication (x10^{-7} kg N eq)**	**Water Consumption (x10^{-5} m^3)**
Vessels (DE)	0.334	*	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Water Consumption – MnSi in slag

Total contribution per input (in %)



Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-5}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-5}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-6}$ kg P eq)	Marine Eutrophication ($x10^{-7}$ kg N eq)	Water Consumption ($x10^{-5}$ m^3)
Vessels (DE)	0.334	*	109	374	0	0	0
Marine gas oil (IE)	0.0676	106	17.6	52.2	57.4	7.54	18.3
Natural gas (DE)	0.361	7.08	*	*	0	0	0
Bituminous coal (DE)	0.577	69.2	106	360	0	0	*
Electricity (Texas) (IE)	0.0174	6.68	3.78	*	14.3	11.7	19.4
Bituminous coal (IE)	0.0986	26.5	23.7	73.9	214	130	19.1
Natural gas (IE)	0.0594	39.6	7.03	19	7.64	7.21	10.1
Transport vessels (IE)	*	2.76	*	*	5.68	4.45	10.5
Transshipment vessels (IE)	*	3.16	*	*	6.52	5.11	12.0
Silica flux (IE)	*	3.17	*	*	*	2.72	6.94
Water usage (IE)	*	*	*	*	*	*	323
Remaining processes (<1%)*	0.0338	2.76	8.62	24.3	6.01	2.99	0.284
TOTAL	1.55	267	276	903	311	172	420

* represents less than 1%, included in the remaining process (1% cut-off)

Overall results – midpoint impact categories for 1 kg of MnSi in Slag

Impact category	Unit	Total
Global warming	kg CO_2 eq	1.5489345
Stratospheric ozone depletion	kg CFC11 eq	2.67E-07
Ionizing radiation	kBq Co-60 eq	0.008894
Ozone formation, Human health	kg NOx eq	0.0036782
Fine particulate matter formation	kg PM2.5 eq	0.002756
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.0037296
Terrestrial acidification	kg SO_2 eq	0.0090335
Freshwater eutrophication	kg P eq	0.0003112
Marine eutrophication	kg N eq	1.72E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.2080735
Freshwater ecotoxicity	kg 1,4-DCB	0.0197767
Marine ecotoxicity	kg 1,4-DCB	0.0264775
Human carcinogenic toxicity	kg 1,4-DCB	0.0541511
Human non-carcinogenic toxicity	kg 1,4-DCB	0.4371574
Land use	m^2a crop eq	0.0177845
Mineral resource scarcity	kg Cu eq	0.262664
Fossil resource scarcity	kg oil eq	0.3723325
Water consumption	m^3	0.0042021

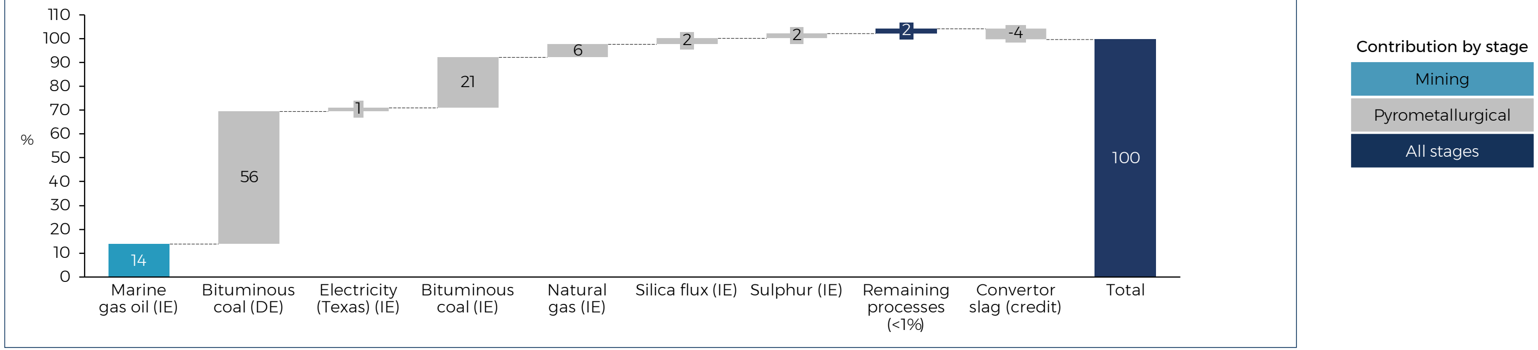
Appendix 3

Life Cycle Impact Assessment

b) Ni/Cu/Co matte – TMC NORI-D results

Input contributions for Ozone depletion – Ni/Cu/Co in matte

Total contribution per input (in %)



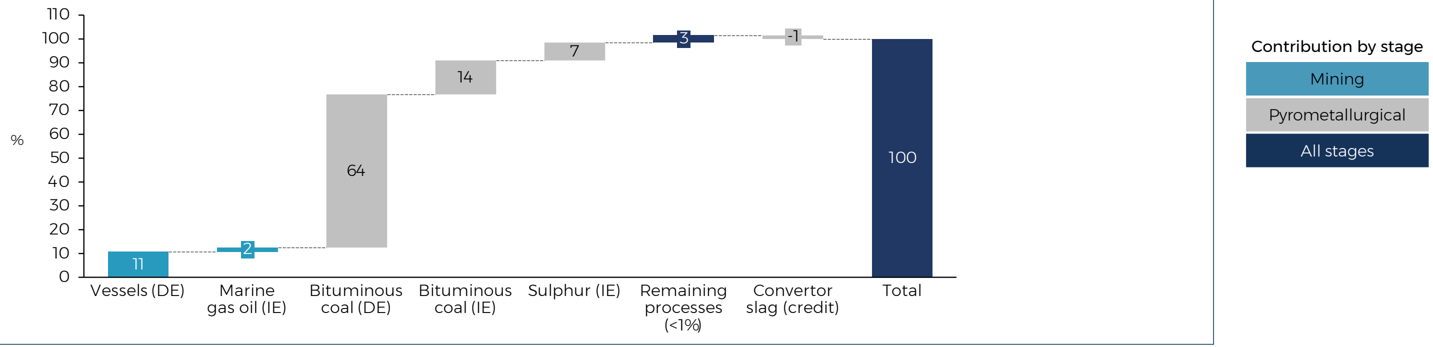
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-6}$ kg N eq)	Water Consumption ($x10^{-5}$ m^3)
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Fine Particulate Matter Formation – Ni/Cu/Co in matte

Total contribution per input (in %)



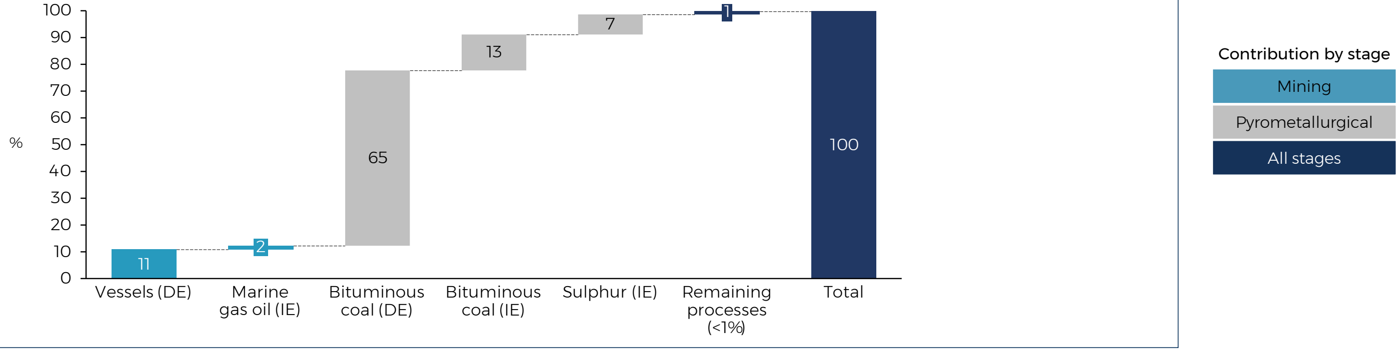
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-6}$ kg N eq)	Water Consumption ($x10^{-5}$ m^3)
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Terrestrial Acidification – Ni/Cu/Co in matte

Total contribution per input (in %)



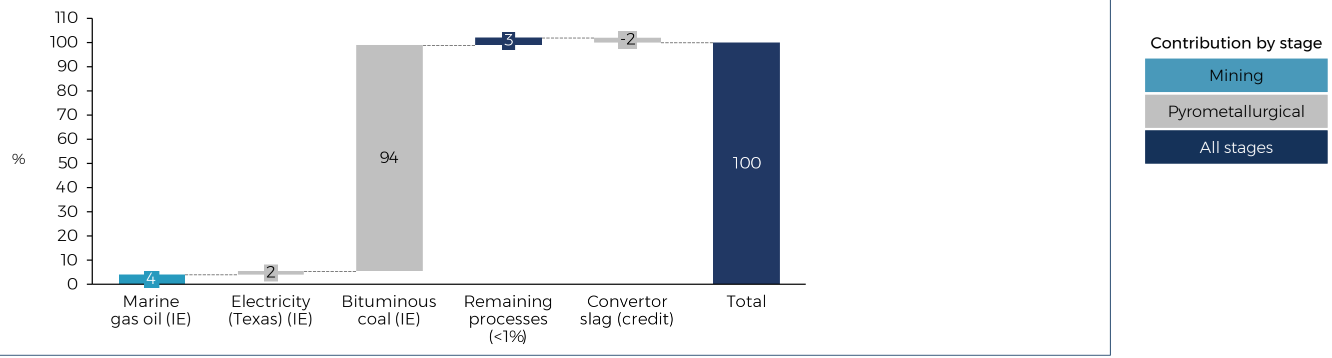
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-6} kg N eq)	Water Consumption (x10^{-5} m^3)
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Freshwater Eutrophication – Ni/Cu/Co in matte

Total contribution per input (in %)



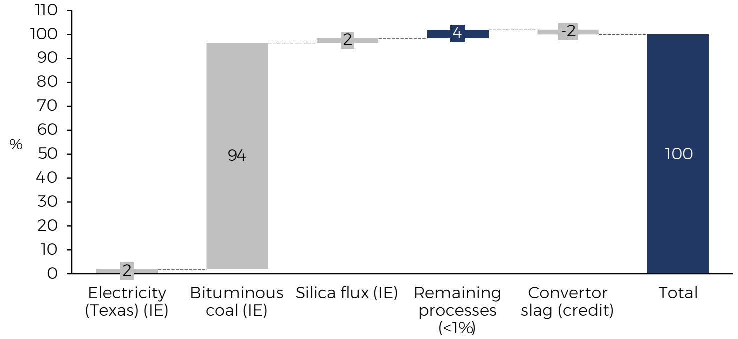
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-6}$ kg N eq)	Water Consumption ($x10^{-5}$ m^3)
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Marine Eutrophication – Ni/Cu/Co in matte

Total contribution per input (in %)



Contribution by stage

- Mining
- Pyrometallurgical
- All stages

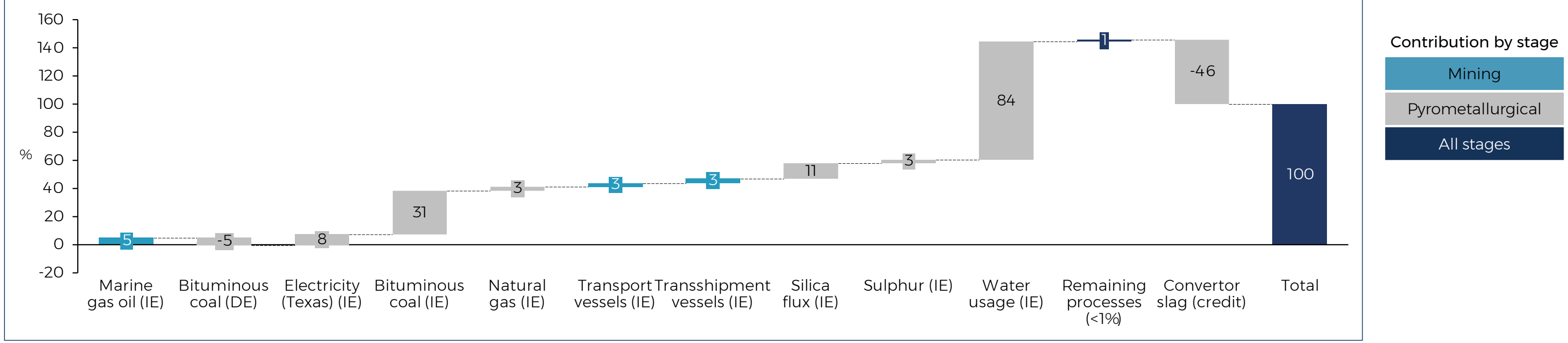
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-6} kg N eq)	Water Consumption (x10^{-5} m^3)
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Water Consumption – Ni/Cu/Co in matte

Total contribution per input (in %)



Input contribution (in absolute values)

	GWP (kg CO_2 eq)	**Ozone Depletion ($x10^{-9}$ kg CFC11 eq)**	**Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)**	**Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)**	**Freshwater Eutrophication ($x10^{-5}$ kg P eq)**	**Marine Eutrophication ($x10^{-6}$ kg N eq)**	**Water Consumption ($x10^{-5}$ m^3)**
Vessels (DE)	0.320	0	10.5	35.8	0	0	0
Marine gas oil (IE)	0.0648	102	1.69	5.00	5.50	*	17.5
Natural gas (DE)	0.371	*	*	*	0	0	0
Bituminous coal (DE)	3.44	157	62.9	214	0	0	-19.1
Electricity (Texas) (IE)	*	9.72	*	*	2.08	1.70	28.3
Bituminous coal (IE)	0.587	157	14.1	44.0	127	77.7	114
Natural gas (IE)	0.0610	40.7	*	*	*	*	10.4
Transport vessels (IE)	*	*	*	*	*	*	10.0
Transshipment vessels (IE)	*	*	*	*	*	*	11.5
Silica flux (IE)	*	18.1	*	*	*	1.55	39.6
Sulphur (IE)	*	13.5	7.18	24.5	*	*	9.82
Water usage (IE)	*	*	*	*	*	*	310
Convertor slag (credit)	-0.0655	-32.5	-1.31	*	-2.83	-1.65	-168
Remaining processes (<1%)*	0.132	15.6	2.91	3.78	4.13	2.96	3.34
TOTAL	4.91	7.36	97.9	327	136	82.2	368

* represents less than 1%, included in the remaining process (1% cut-off)

Overall results - midpoint impact categories for 1 kg of Ni/Cu/Co in matte

Impact category	**Unit**	**Total**
Global warming	kg CO_2 eq	4.9081465
Stratospheric ozone depletion	kg CFC11 eq	7.36E-07
Ionizing radiation	kBq Co-60 eq	0.0109551
Ozone formation, Human health	kg NOx eq	0.01206715
Fine particulate matter formation	kg PM2.5 eq	0.00979268
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.01218131
Terrestrial acidification	kg SO_2 eq	0.03273038
Freshwater eutrophication	kg P eq	0.00136124
Marine eutrophication	kg N eq	8.22E-05
Terrestrial ecotoxicity	kg 1,4-DCB	2.9483432
Freshwater ecotoxicity	kg 1,4-DCB	0.05479024
Marine ecotoxicity	kg 1,4-DCB	0.07508595
Human carcinogenic toxicity	kg 1,4-DCB	0.13215165
Human non-carcinogenic toxicity	kg 1,4-DCB	1.9167277
Land use	m^2a crop eq	0.05760257
Mineral resource scarcity	kg Cu eq	0.25220379
Fossil resource scarcity	kg oil eq	1.0267126
Water consumption	m^3	0.00367553

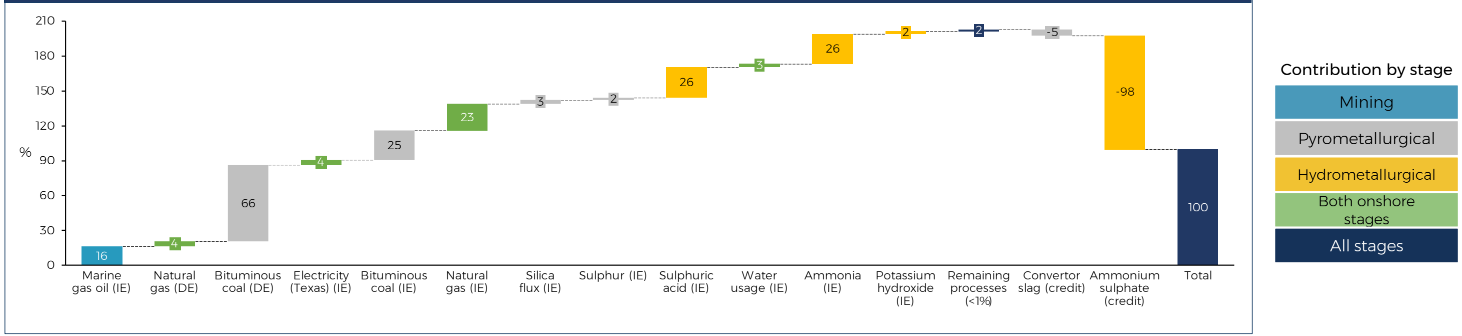
Appendix 4

Life Cycle Impact Assessment

c) Nickel in nickel sulphate – TMC NORI-D results

Input contributions for Ozone Depletion – Ni in Nickel Sulphate

Total contribution per input (in %)



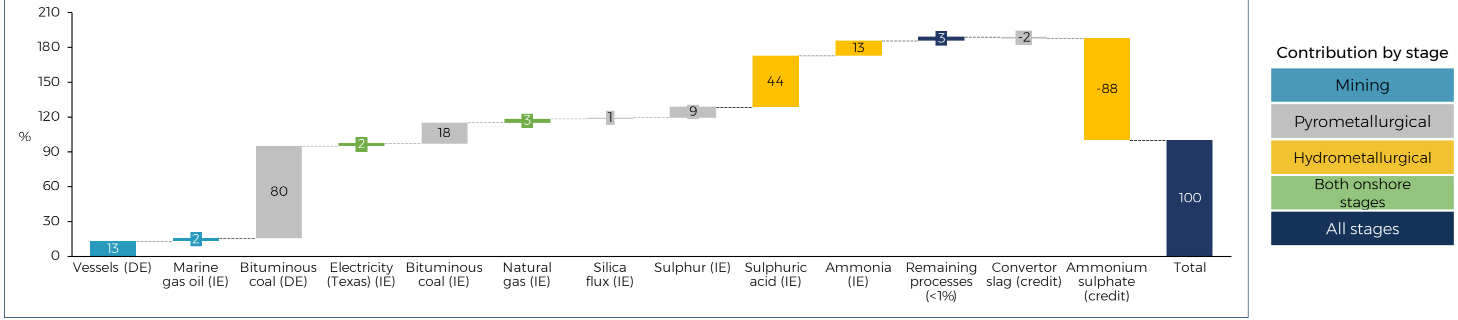
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Fine Particulate Matter Formation – Ni in Nickel Sulphate

Total contribution per input (in %)



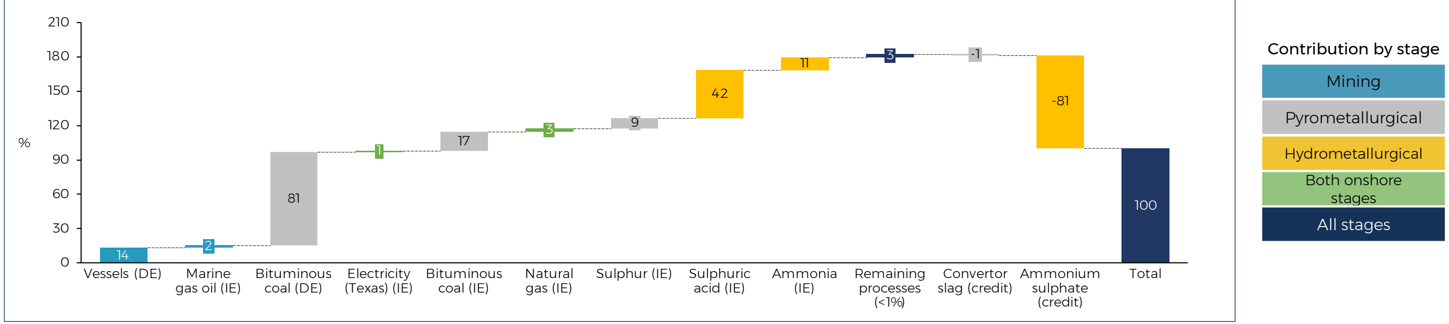
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Terrestrial Acidification – Ni in Nickel Sulphate

Total contribution per input (in %)



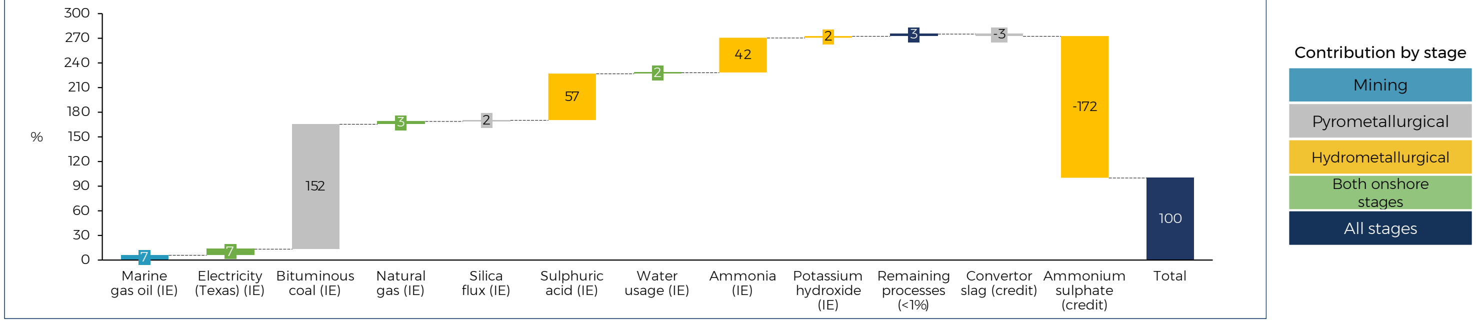
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Freshwater Eutrophication – Ni in Nickel Sulphate

Total contribution per input (in %)



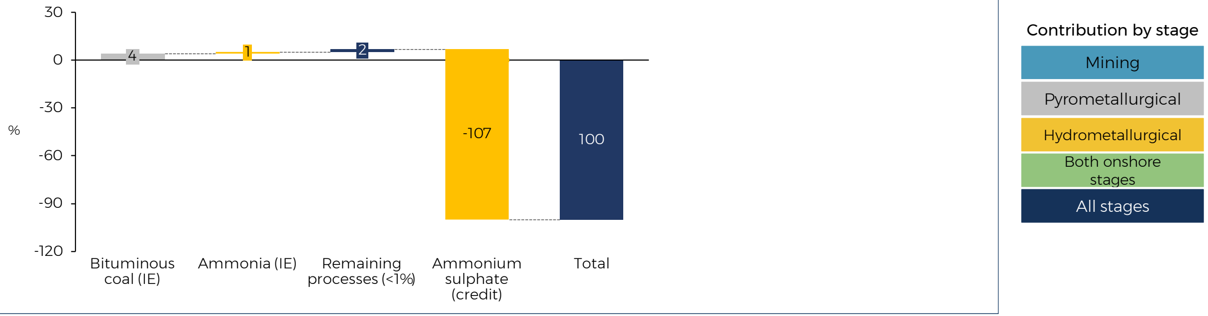
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($\times10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($\times10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($\times10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($\times10^{-5}$ kg P eq)	Marine Eutrophication ($\times10^{-5}$ kg N eq)	Water Consumption ($\times10^{-3}$ m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Marine Eutrophication – Ni in Nickel Sulphate

Total contribution per input (in %)



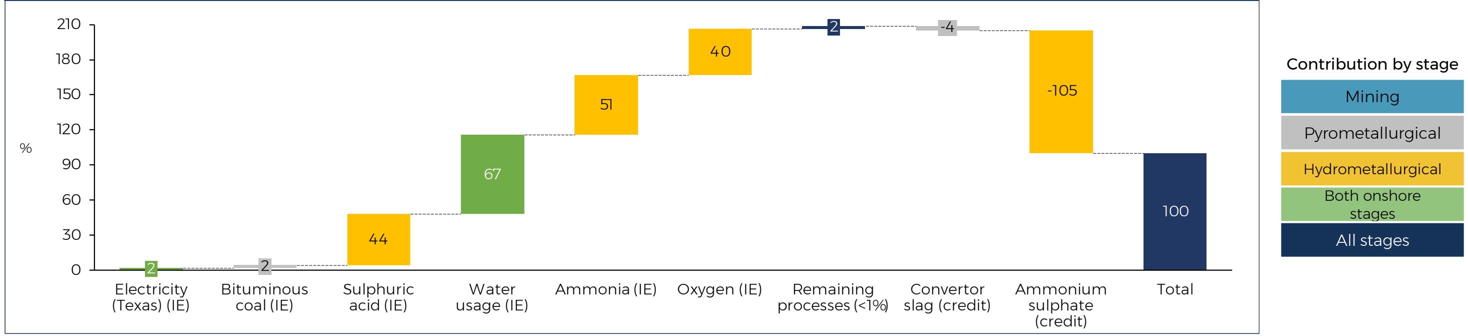
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Water Consumption – Ni in Nickel Sulphate

Total contribution per input (in %)



Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.375	0	12.3	42.0	0	0	0
Marine gas oil (IE)	0.076	11.9	1.98	5.87	6.45	*	*
Natural gas (DE)	1.55	3.04	*	*	0	0	0
Bituminous coal (DE)	4.03	48.3	73.8	251	0	0	*
Electricity (Texas) (IE)	0.0833	3.21	1.82	3.47	6.86	*	0.934
Bituminous coal (IE)	0.689	18.5	16.5	51.6	149	9.11	1.34
Natural gas (IE)	0.255	17.0	3.02	8.16	3.28	*	*
Silica flux (IE)	*	2.12	1.13	*	1.52	*	*
Sulphur (IE)	*	1.58	8.42	28.8	*	*	*
Sulphuric acid (IE)	0.289	19.3	40.6	130	55.6	*	24.1
Water usage (IE)	*	2.11	*	*	1.84	*	36.7
Ammonia (IE)	1.61	18.8	12.2	33.5	41.2	2.46	27.9
Potassium hydroxide (IE)	*	1.67	*	*	1.93	*	*
Oxygen (IE)	0	0	0	0	0	0	21.7
Convertor slag (credit)	-0.0768	-3.81	-1.54	-3.33	-3.31	*	-1.97
Ammonium sulphate (credit)	-2.93	-71.6	-80.8	-251	-169	-229	-57.3
Remaining processes (<1%)*	0.210	1.22	2.92	8.96	3.10	3.23	1.22
TOTAL	0.375	73.3	92.3	309	98.4	-215	54.6

* represents less than 1%, included in the remaining process (1% cut-off)

Overall results - midpoint impact categories for 1 kg of Nickel in Nickel Sulphate

Impact category	Unit	Total
Global warming	kg CO_2 eq	6.1655693
Stratospheric ozone depletion	kg CFC11 eq	7.33E-07
Ionizing radiation	kBq Co-60 eq	-0.0468078
Ozone formation, Human health	kg NOx eq	0.01278801
Fine particulate matter formation	kg PM2.5 eq	0.00922689
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.01278416
Terrestrial acidification	kg SO_2 eq	0.03087316
Freshwater eutrophication	kg P eq	0.00098393
Marine eutrophication	kg N eq	-0.0021456
Terrestrial ecotoxicity	kg 1,4-DCB	-12.903241
Freshwater ecotoxicity	kg 1,4-DCB	-0.1781432
Marine ecotoxicity	kg 1,4-DCB	-0.1749404
Human carcinogenic toxicity	kg 1,4-DCB	-0.002728
Human non-carcinogenic toxicity	kg 1,4-DCB	-0.979332
Land use	m^2a crop eq	0.02912704
Mineral resource scarcity	kg Cu eq	0.27882357
Fossil resource scarcity	kg oil eq	1.3384597
Water consumption	m^3	0.05456705

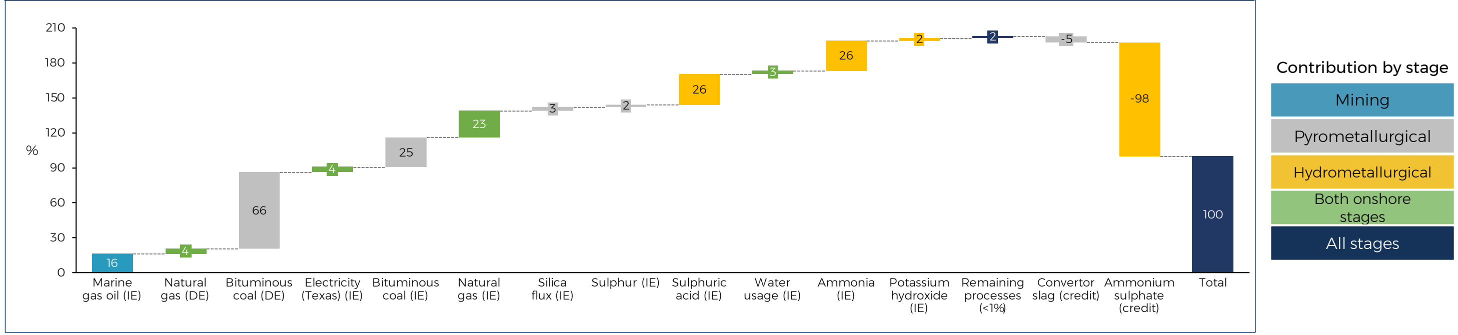
Appendix 5

Life Cycle Impact Assessment

d) copper cathode – TMC NORI-D results

Input contributions for Ozone Depletion – Cu cathode

Total contribution per input (in %)



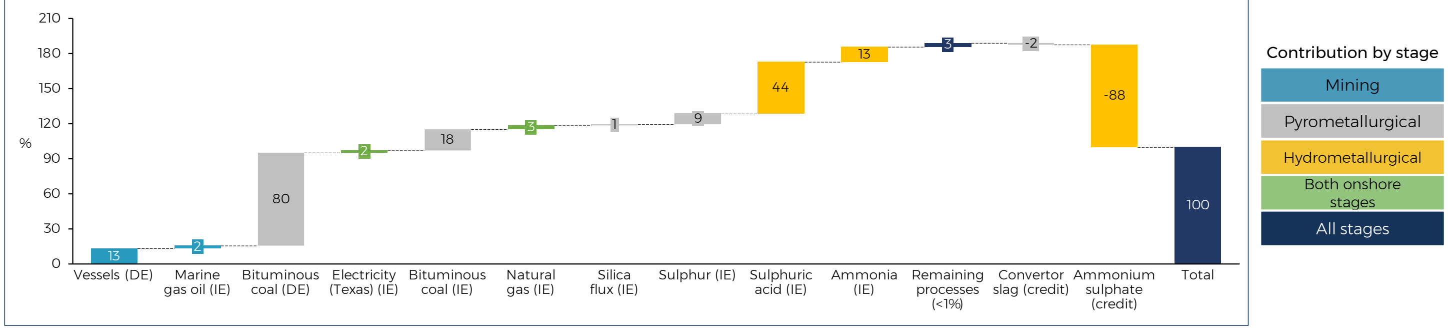
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-5}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-6}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-4}$ m^3)
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Fine Particulate Matter Formation – Cu cathode

Total contribution per input (in %)



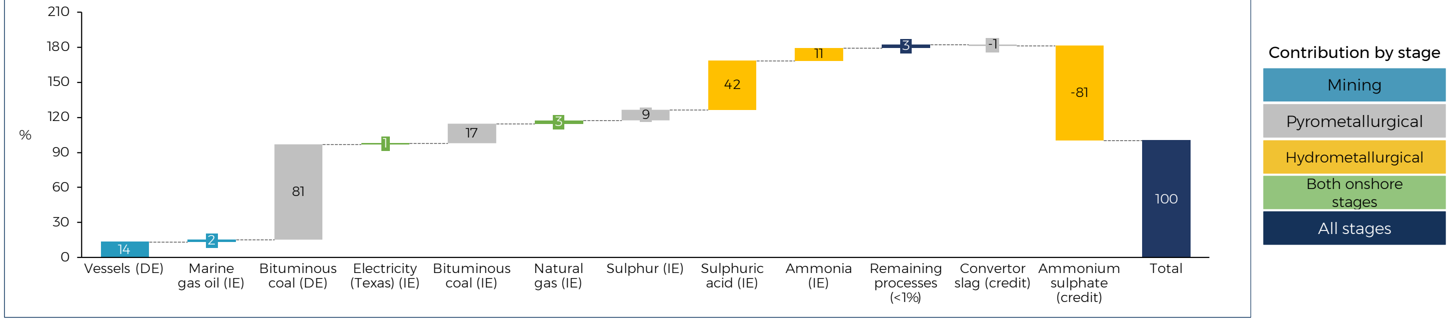
Input contribution (in absolute values)

	GWP (kg CO$_2$ eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO$_2$ eq)	Freshwater Eutrophication (x10^{-6} kg P eq)	Marine Eutrophication (x10^{-5} kg N eq)	Water Consumption (x10^{-4} m^3)
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Terrestrial Acidification– Cu cathode

Total contribution per input (in %)



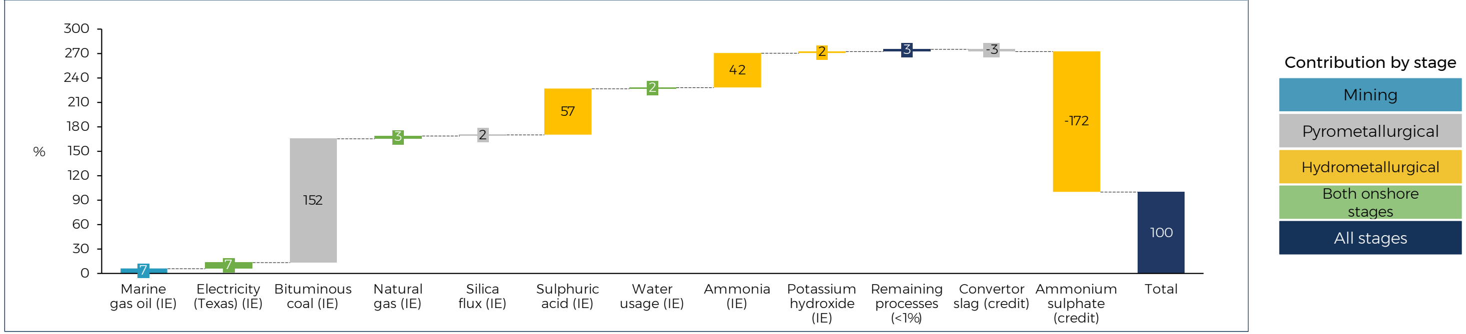
Input contribution (in absolute values)

	GWP ($kg\ CO_2$ eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-5}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-6}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-4}$ m^3)
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Freshwater Eutrophication– Cu cathode

Total contribution per input (in %)



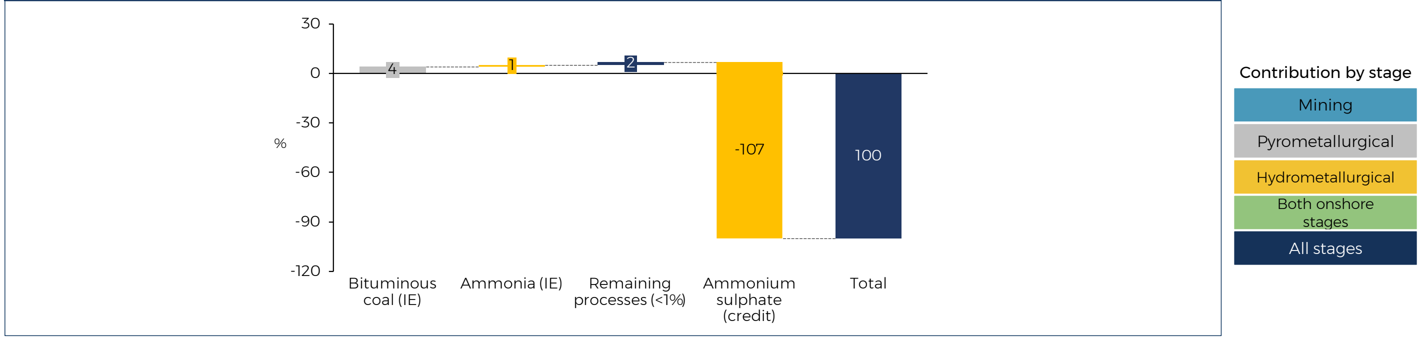
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-9} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-5} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-6} kg P eq)	Marine Eutrophication (x10^{-5} kg N eq)	Water Consumption (x10^{-4} m^3)
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Marine Eutrophication– Cu cathode

Total contribution per input (in %)



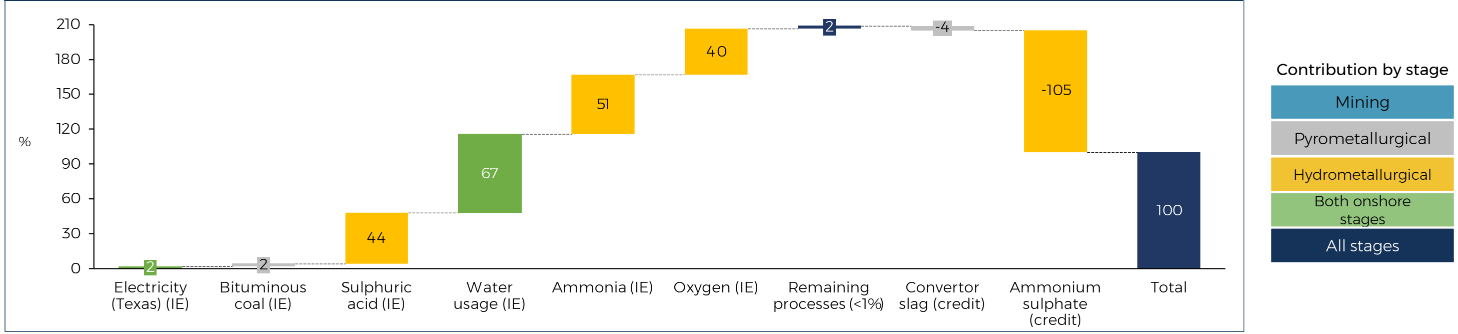
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-5}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-6}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-4}$ m^3)
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Water Consumption – Cu cathode

Total contribution per input (in %)



Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-9}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-5}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-6}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-4}$ m^3)
Vessels (DE)	0.173	0	56.4	19.3	0	0	0
Marine gas oil (IE)	0.0349	55.0	9.10	2.70	29.6	*	*
Natural gas (DE)	0.713	14.0	*	*	0	0	0
Bituminous coal (DE)	1.85	222	339	116	0	0	*
Electricity (Texas) (IE)	0.0383	14.8	8.35	1.60	31.6	*	4.29
Bituminous coal (IE)	0.317	85.0	76.0	23.7	686	4.19	6.15
Natural gas (IE)	0.117	78.1	13.9	3.75	15.1	*	*
Silica flux (IE)	*	9.75	5.19	*	7.01	*	*
Sulphur (IE)	*	7.27	38.7	13.2	*	*	*
Sulphuric acid (IE)	0.133	88.8	187	59.6	256	*	111
Water usage (IE)	*	9.71	*	*	8.47	*	169
Ammonia (IE)	0.742	86.4	56.2	15.4	190	1.13	128
Potassium hydroxide (IE)	*	7.70	*	*	8.87	*	*
Oxygen (IE)	0	0	0	0	0	0	99.6
Convertor slag (credit)	-0.0353	-17.5	-7.07	-1.53	-15.2	*	-9.05
Ammonium sulphate (credit)	-1.35	-329	-372	-115	-779	-105	-264
Remaining processes (<1%)*	0.0965	5.59	13.4	4.12	14.3	1.48	5.59
TOTAL	2.84	337	424	142	453	-98.7	251

* represents less than 1%, included in the remaining process (1% cut-off)

Overall results - midpoint impact categories for 1 kg of Copper Cathode

Impact category	**Unit**	**Total**
Global warming	kg CO_2 eq	2.8360068
Stratospheric ozone depletion	kg CFC11 eq	3.37E-07
Ionizing radiation	kBq Co-60 eq	-0.0215304
Ozone formation, Human health	kg NOx eq	0.0058822
Fine particulate matter formation	kg PM2.5 eq	0.0042441
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.0058804
Terrestrial acidification	kg SO_2 eq	0.0142009
Freshwater eutrophication	kg P eq	0.0004526
Marine eutrophication	kg N eq	-0.0009869
Terrestrial ecotoxicity	kg 1,4-DCB	-5.9351664
Freshwater ecotoxicity	kg 1,4-DCB	-0.0819414
Marine ecotoxicity	kg 1,4-DCB	-0.0804682
Human carcinogenic toxicity	kg 1,4-DCB	-0.0012548
Human non-carcinogenic toxicity	kg 1,4-DCB	-0.4504681
Land use	m^2a crop eq	0.0133977
Mineral resource scarcity	kg Cu eq	0.1282518
Fossil resource scarcity	kg oil eq	0.6156578
Water consumption	m^3	0.0250995

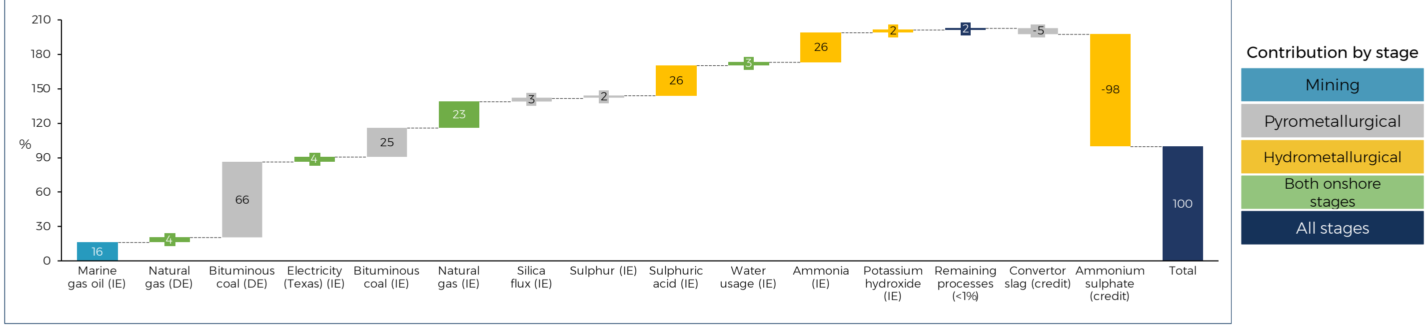
Appendix 6

Life Cycle Impact Assessment

e) cobalt in cobalt sulphate – TMC NORI-D results

Input contributions for Ozone Depletion – Co in Cobalt Sulphate

Total contribution per input (in %)



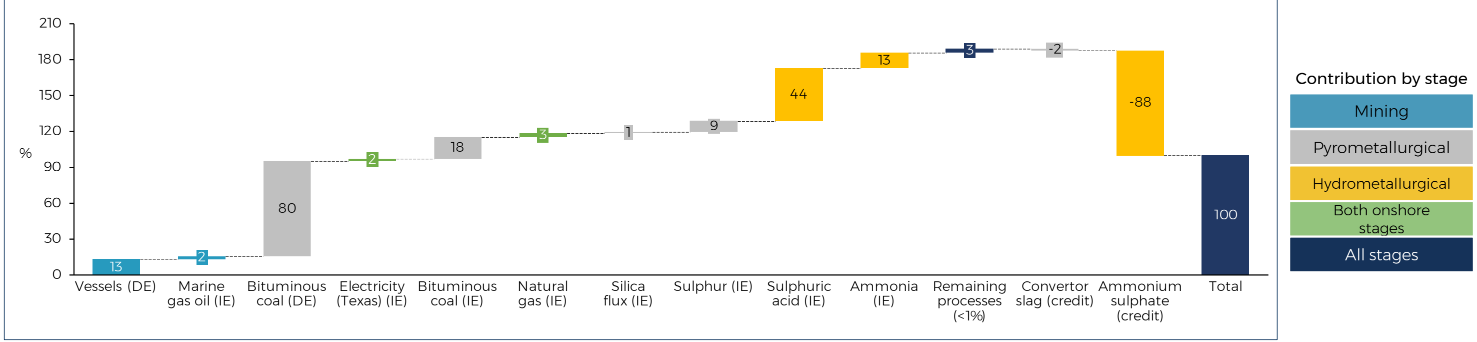
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-8} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-5} kg N eq)	Water Consumption (x10^{-3} m^3)
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Fine Particulate Matter Formation – Co in Cobalt Sulphate

Total contribution per input (in %)



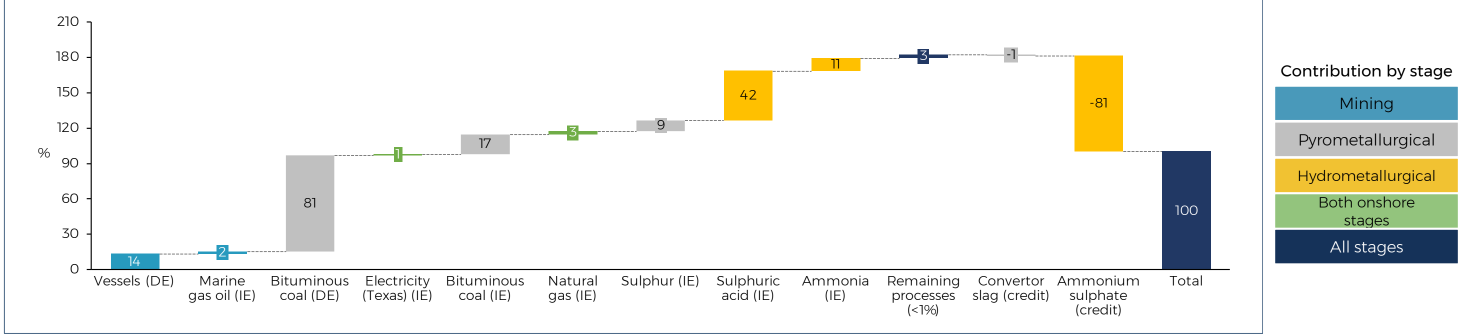
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	**Ozone Depletion ($x10^{-8}$ kg CFC11 eq)**	**Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)**	**Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)**	**Freshwater Eutrophication ($x10^{-5}$ kg P eq)**	**Marine Eutrophication ($x10^{-5}$ kg N eq)**	**Water Consumption ($x10^{-3}$ m^3)**
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Terrestrial Acidification– Co in Cobalt Sulphate

Total contribution per input (in %)



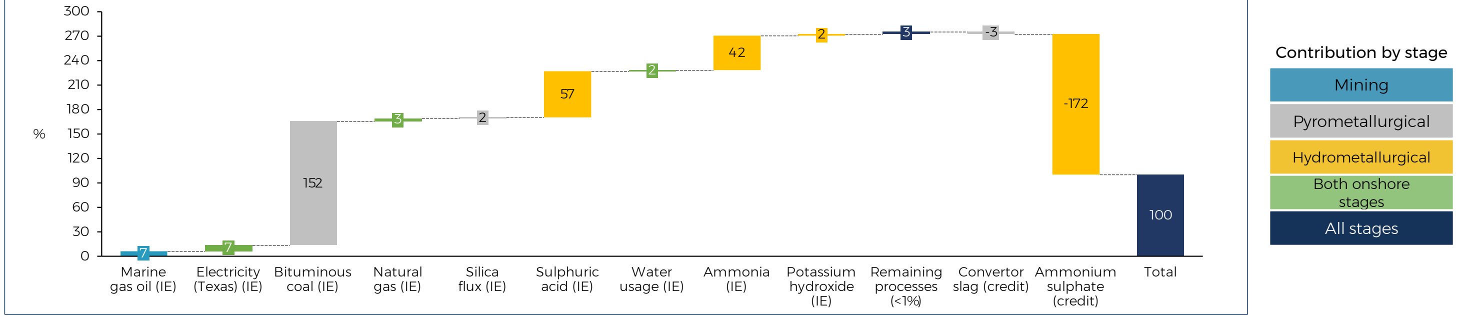
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-8} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-5} kg N eq)	Water Consumption (x10^{-3} m^3)
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Freshwater Eutrophication– Co in Cobalt Sulphate

Total contribution per input (in %)



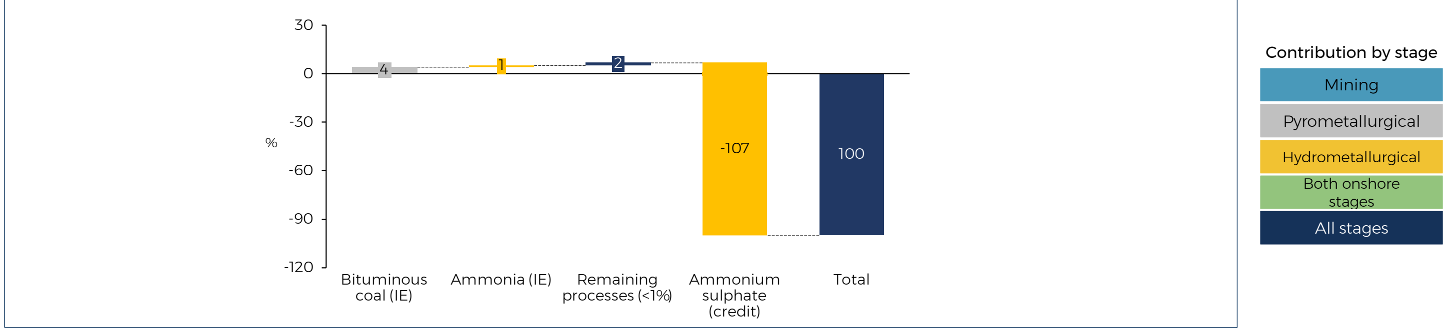
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-8} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine Eutrophication (x10^{-5} kg N eq)	Water Consumption (x10^{-3} m^3)
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Marine Eutrophication– Co in Cobalt Sulphate

Total contribution per input (in %)



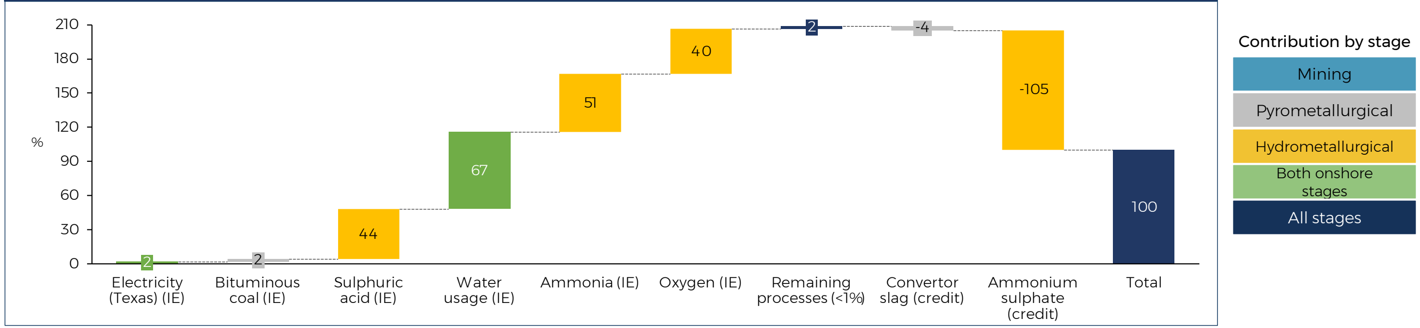
Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion ($x10^{-8}$ kg CFC11 eq)	Fine Particulate Matter Formation ($x10^{-4}$ kg PM2.5 eq)	Terrestrial Acidification ($x10^{-4}$ kg SO_2 eq)	Freshwater Eutrophication ($x10^{-5}$ kg P eq)	Marine Eutrophication ($x10^{-5}$ kg N eq)	Water Consumption ($x10^{-3}$ m^3)
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

* represents less than 1%, included in the remaining process (1% cut-off)

Input contributions for Water Consumption – Co in Cobalt Sulphate

Total contribution per input (in %)



Input contribution (in absolute values)

	GWP (kg CO_2 eq)	Ozone Depletion (x10^{-8} kg CFC11 eq)	Fine Particulate Matter Formation (x10^{-4} kg PM2.5 eq)	Terrestrial Acidification (x10^{-4} kg SO_2 eq)	Freshwater Eutrophication (x10^{-5} kg P eq)	Marine eutrophication (x10^{-5} kg N eq)	Water consumption (x10^{-3} m^3)
Vessels (DE)	0.999	0	32.7	112	0	0	0
Marine gas oil (IE)	0.202	31.8	5.26	15.6	17.2	*	*
Natural gas (DE)	4.12	8.09	*	*	0	0	0
Bituminous coal (DE)	10.7	129	196	668	0	0	*
Electricity (Texas) (IE)	0.222	8.54	4.83	9.24	18.3	*	2.49
Bituminous coal (IE)	1.83	49.2	44.0	137	397	24.2	3.56
Natural gas (IE)	0.678	45.2	8.04	21.7	8.73	*	*
Silica flux (IE)	*	5.64	3.00	*	4.05	*	*
Sulphur (IE)	*	4.21	22.4	76.5	*	*	*
Sulphuric acid (IE)	0.768	51.4	108	345	148	*	64.2
Water usage (IE)	*	5.62	*	*	4.90	*	97.7
Ammonia (IE)	4.29	50.0	32.5	89.2	110	6.55	74.3
Potassium hydroxide (IE)	*	4.45	*	*	5.13	*	*
Oxygen (IE)	0	0	0	0	0	0	57.6
Convertor slag (credit)	-0.204	-10.2	-4.09	-8.86	-8.82	*	-5.23
Ammonium sulphate (credit)	-7.79	-191	-215	-668	-451	-610	-153
Remaining processes (<1%)*	0.558	3.23	7.76	23.8	8.25	8.59	3.23
TOTAL	16.4	195	246	822	262	-571	145

* represents less than 1%, included in the remaining process (1% cut-off)

Overall results - midpoint impact categories for 1 kg of Cobalt in Cobalt Sulphate

Impact category	**Unit**	**Total**
Global warming	kg CO_2 eq	16.409917
Stratospheric ozone depletion	kg CFC11 eq	1.95E-06
Ionizing radiation	kBq Co-60 eq	-0.124581
Ozone formation, Human health	kg NOx eq	0.03403582
Fine particulate matter formation	kg PM2.5 eq	0.02455775
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.03402556
Terrestrial acidification	kg SO_2 eq	0.0821702
Freshwater eutrophication	kg P eq	0.00261878
Marine eutrophication	kg N eq	-0.0057105
Terrestrial ecotoxicity	kg 1,4-DCB	-34.342509
Freshwater ecotoxicity	kg 1,4-DCB	-0.4741354
Marine ecotoxicity	kg 1,4-DCB	-0.465611
Human carcinogenic toxicity	kg 1,4-DCB	-0.0072607
Human non-carcinogenic toxicity	kg 1,4-DCB	-2.6065324
Land use	m^2a crop eq	0.07752283
Mineral resource scarcity	kg Cu eq	0.74210043
Fossil resource scarcity	kg oil eq	3.5623658
Water consumption	m^3	0.14523245

Appendix 7

TMC NORI-D results versus land-based mining and processing routes

Data quality requirements

Data quality requirements of land-based routes

Data quality checks are a requirement of comparative studies. This study is intended for general public release and as such a qualitative review of the dataset is complemented by a third-party revision. For completeness, the data quality of the **land-based mining and processing routes** has been assessed against ten data quality categories defined in ISO 14044.

Quality Categories	Details
Time related coverage	Foreground data provided to Benchmark by two cobalt and nickel specialists (chemical engineers) in 2022 and background data taken from Ecoinvent 2021 (version 3.8). Complementary data for cobalt mining was taken from GREET[1] 2018.
Geographical coverage	Country electricity mixes: Indonesia, Australia, Democratic Republic of Congo and China. Ecoinvent: global and rest-of-world.
Technology coverage	Technological representativeness has been defined as a present-day average. Some aspects of technology within the system process are likely to change to a new average within 5-10 years.
Precision	Foreground data values given are averages, due to technical variances per asset.
Completeness	100% of processes in the system boundary are defined and given a value.
Representatives	The dataset is reflective of true cobalt, nickel and copper production values to a moderate degree, because of a compromised sample size.
Consistency	The study methodology has been applied uniformly to all components of the analysis to a high degree.
Reproducibility	This data quality point would score low due to the exclusive use of Benchmark foreground data.
Sources of the data	Reliability of the foreground source is dependant on the extensive experience and knowledge gathered by trusted specialists. The background data relies on peer reviewed data from Ecoinvent.
Uncertainty	Uncertainty of the data comes from both foreground and background where averages were used.

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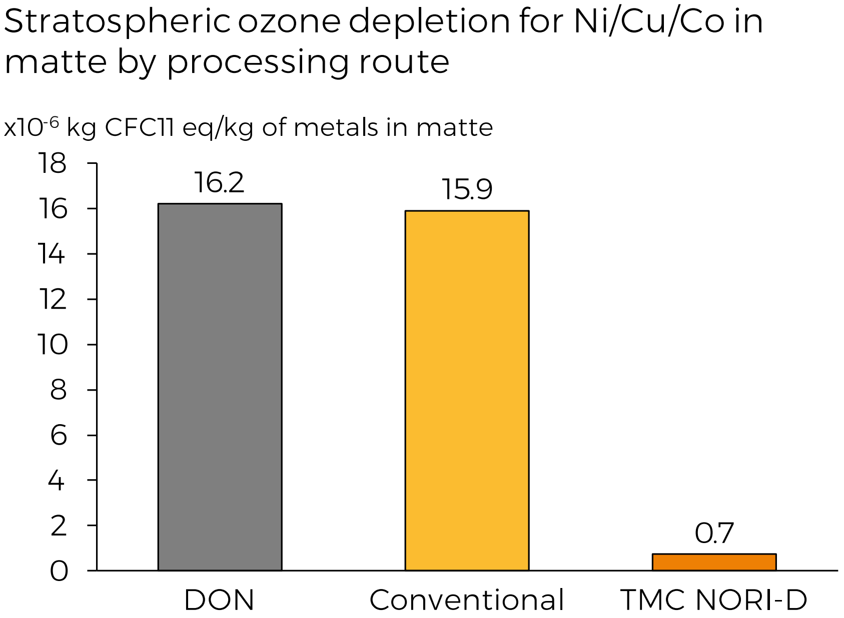
1. GREET, Sept 2018. Link. Accessed October 4th, 2022.

Appendix 8

TMC NORI-D results versus land-based mining and processing routes

a) Ni/Cu/Co matte comparison

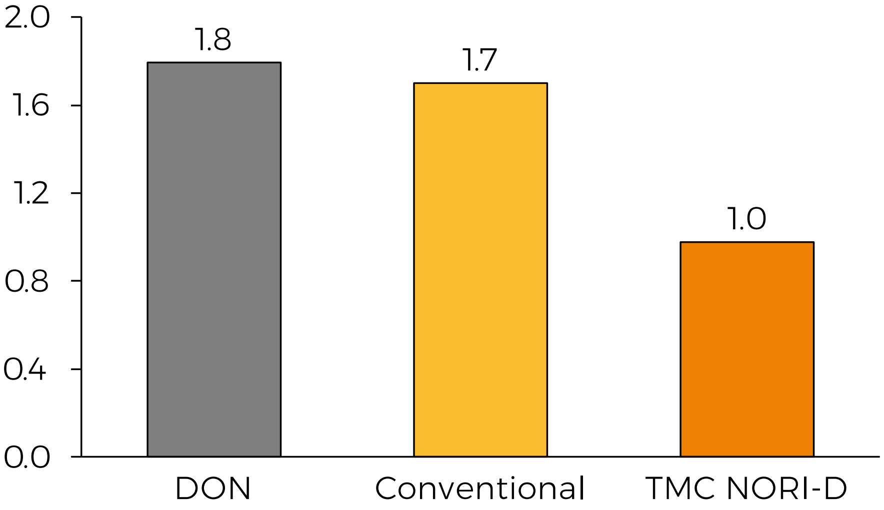
Stratospheric ozone depletion - Ni/Cu/Co in Matte comparison by route



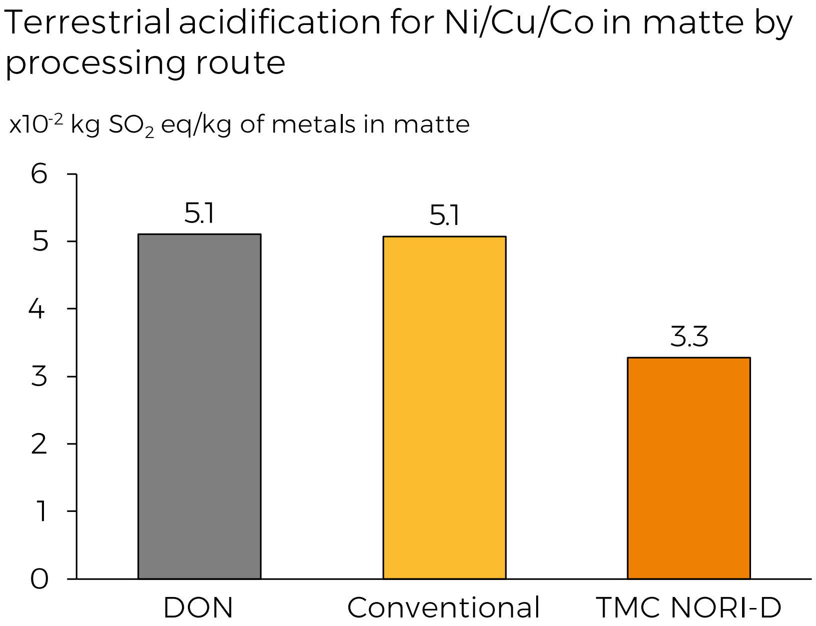
Fine particulate matter formation - Ni/Cu/Co in Matte comparison by route

Fine particulate matter formation for Ni/Cu/Co in matte by processing route

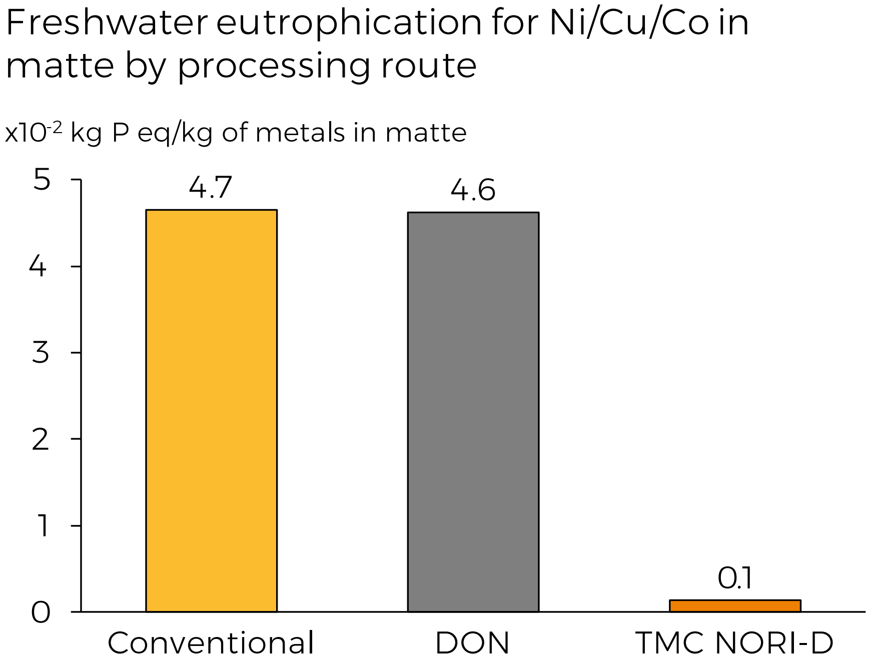
x10^{-2} kg PM2.5 eq/kg of metals in matte



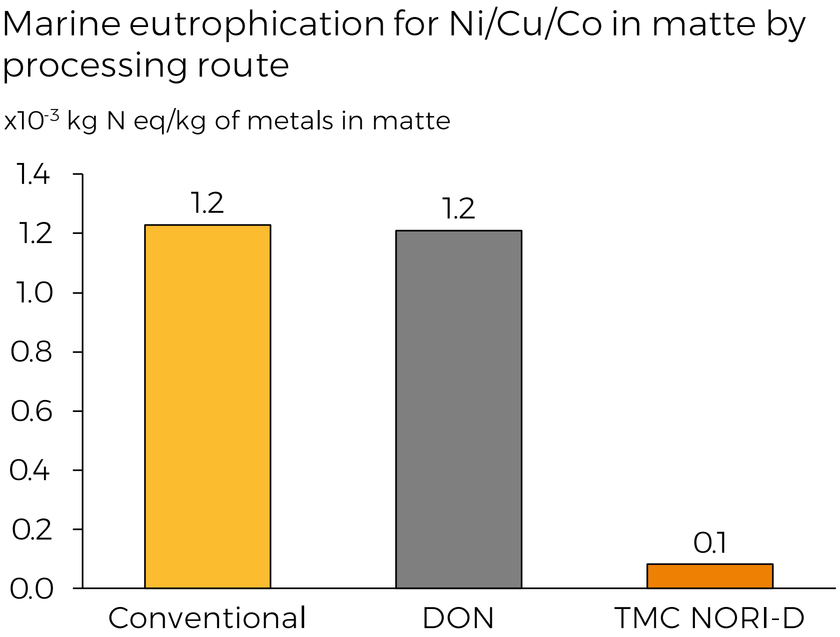
Terrestrial acidification - Ni/Cu/Co in Matte comparison by route



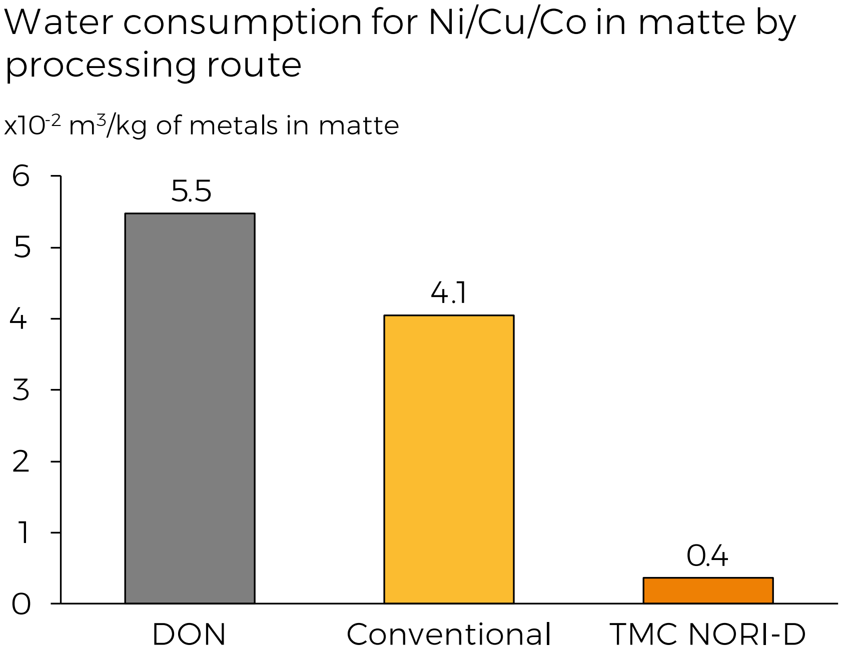
Freshwater eutrophication - Ni/Cu/Co in Matte comparison by route



Marine eutrophication - Ni/Cu/Co in Matte comparison by route



Water consumption – Ni/Cu/Co in Matte comparison by route



Overall results per midpoint impact category - 1 kg of Ni/Cu/Co in matte

Impact category	**Unit**	**Conventional**	**DON**	**TMC NORI-D**
Global warming	kg CO_2 eq	12.647692	13.638042	4.9081465
Stratospheric ozone depletion	kg CFC11 eq	1.59E-05	1.62E-05	7.36E-07
Ionizing radiation	kBq Co-60 eq	0.13348121	0.19162797	0.0109551
Ozone formation, Human health	kg NOx eq	0.087747214	0.089974275	0.0120672
Fine particulate matter formation	kg PM2.5 eq	0.01698648	0.017933981	0.0097927
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.089097526	0.091358441	0.0121813
Terrestrial acidification	kg SO_2 eq	0.050710084	0.051008603	0.0327304
Freshwater eutrophication	kg P eq	0.046526167	0.046202372	0.0013612
Marine eutrophication	kg N eq	0.00123264	0.001210052	8.22E-05
Terrestrial ecotoxicity	kg 1,4-DCB	5.2776831	5.8949773	2.9483432
Freshwater ecotoxicity	kg 1,4-DCB	26.407964	26.403036	0.0547902
Marine ecotoxicity	kg 1,4-DCB	32.753914	32.747111	0.0750859
Human carcinogenic toxicity	kg 1,4-DCB	1.6427291	1.6346254	0.1321517
Human non-carcinogenic toxicity	kg 1,4-DCB	255.56465	255.28477	1.9167277
Land use	m^2a crop eq	44.4733	44.490315	0.0576026
Mineral resource scarcity	kg Cu eq	2.7688389	2.7691906	0.2522038
Fossil resource scarcity	kg oil eq	3.0038294	3.2556771	1.0267126
Water consumption	m^3	0.040538227	0.054732073	0.0036755

Overall results per endpoint impact category - 1 kg of Ni/Cu/Co in matte

Damage category	Unit	Conventional	DON	TMC NORI-D
Human Health	DALY	8.63×10^{-5}	8.78×10^{-5}	1.16×10^{-5}
Ecosystems	species.yr	5.05×10^{-7}	5.09×10^{-7}	2.38×10^{-8}
Resources	USD2013	1.07	1.17	0.25

Appendix 9

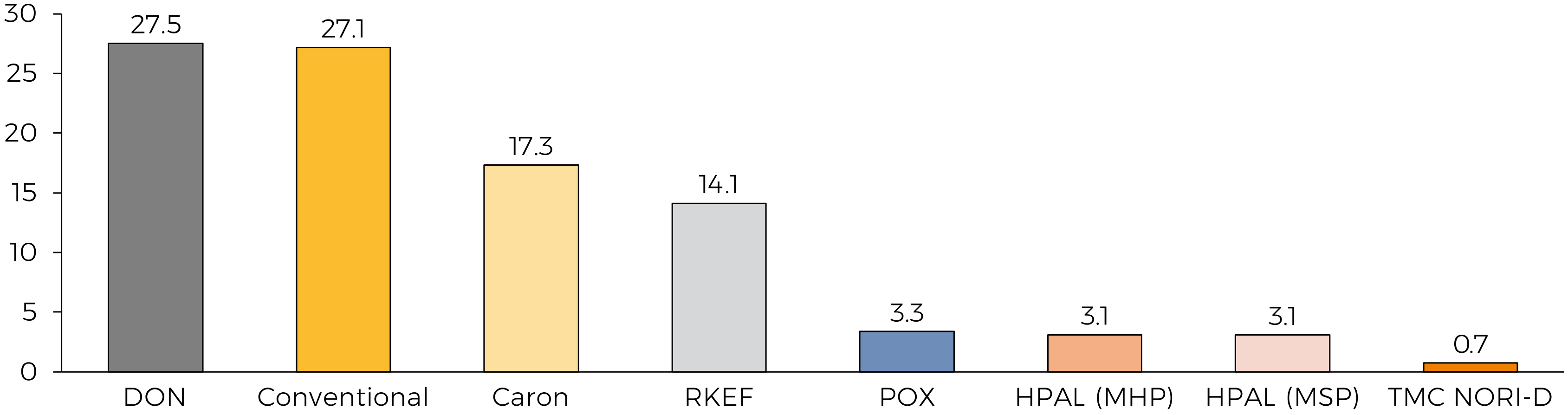
TMC NORI-D results versus land-based mining and processing

b) Nickel in nickel sulphate comparison

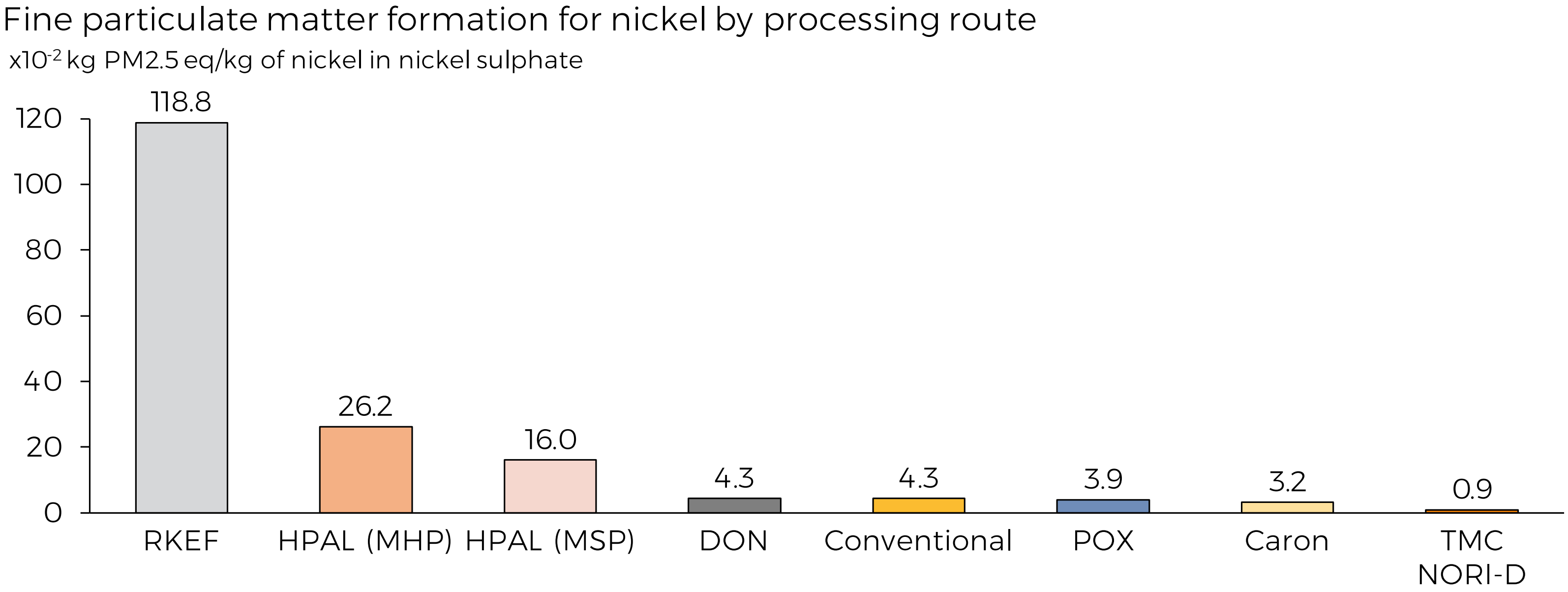
Ozone depletion – Nickel in Nickel Sulphate comparison by route

Stratospheric ozone depletion for nickel by processing route

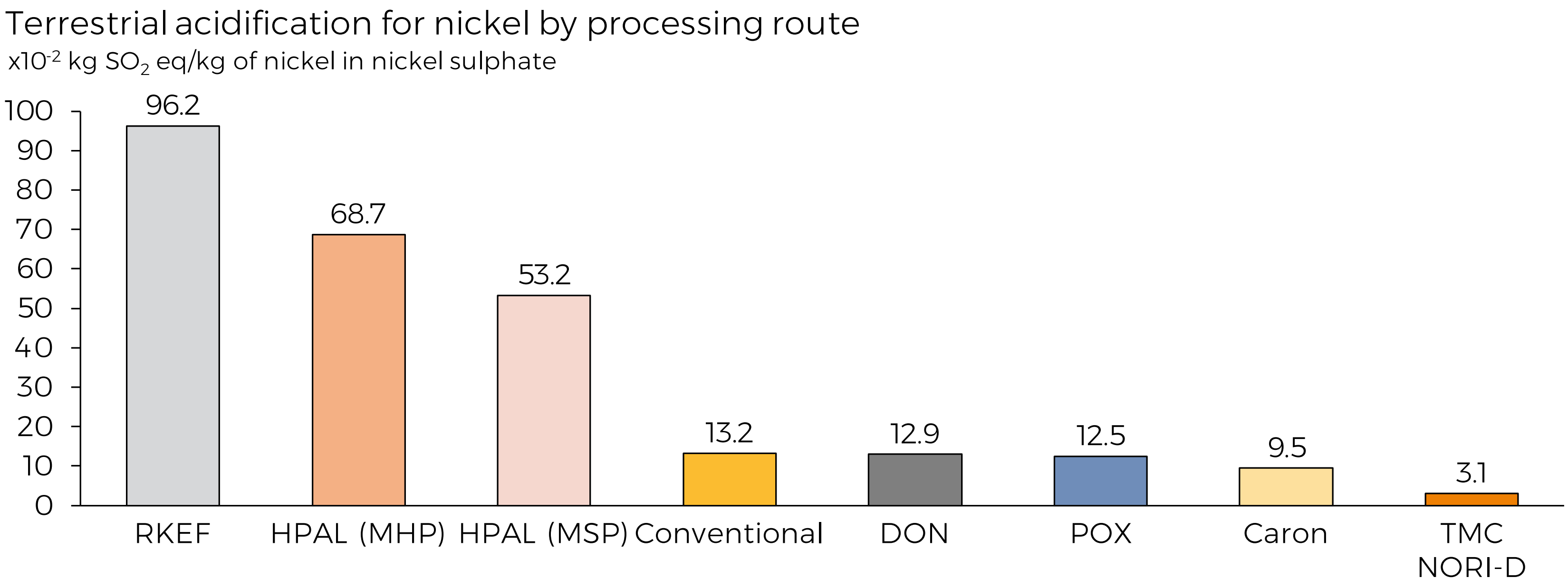
x10^{-6} kg CFC11 eq/kg of nickel in nickel sulphate



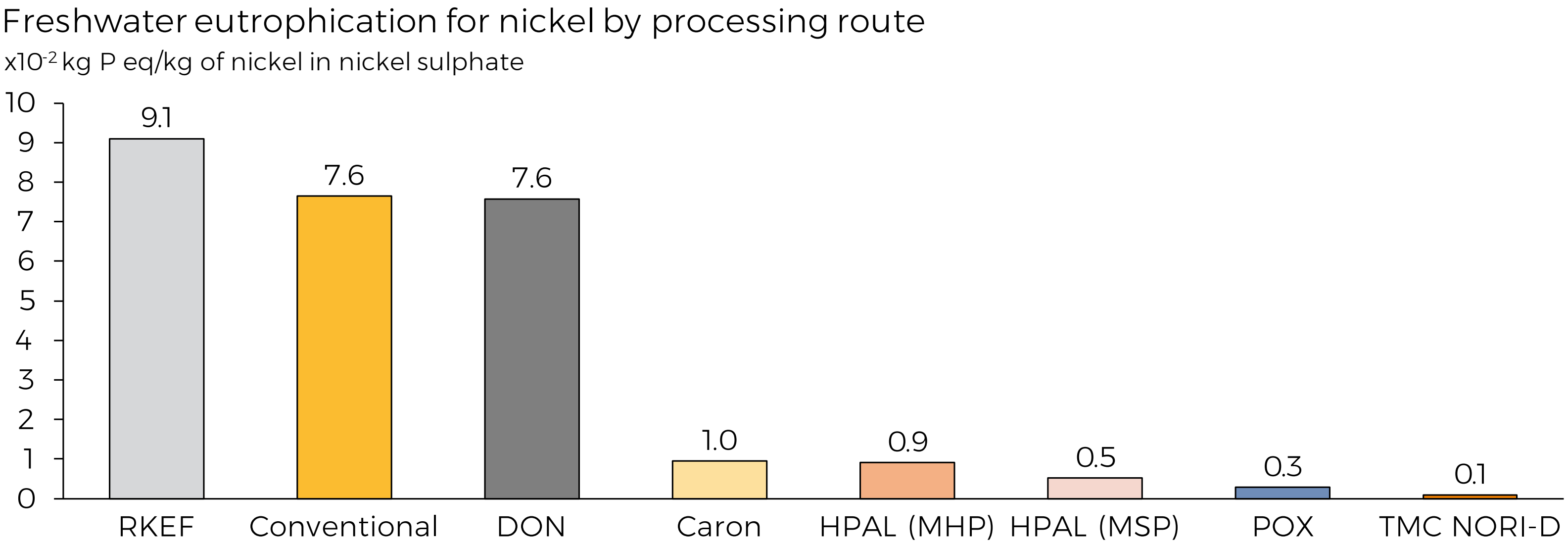
Fine particulate matter formation – Nickel in Nickel Sulphate comparison by route



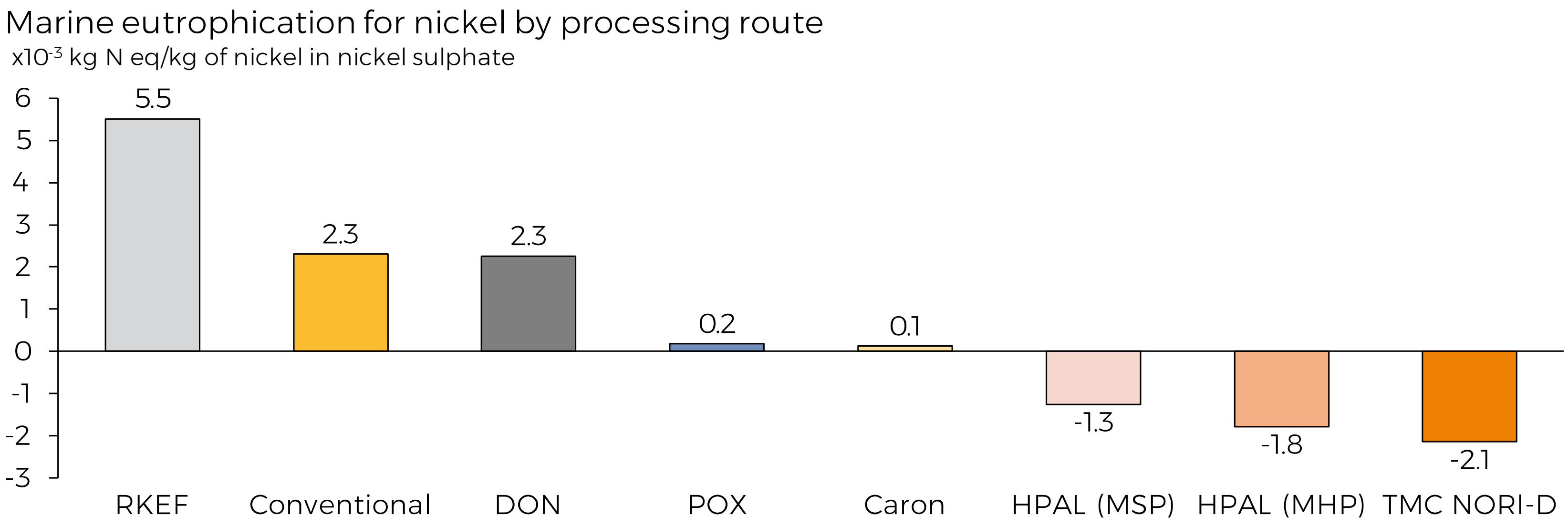
Terrestrial acidification – Nickel in Nickel Sulphate comparison by route



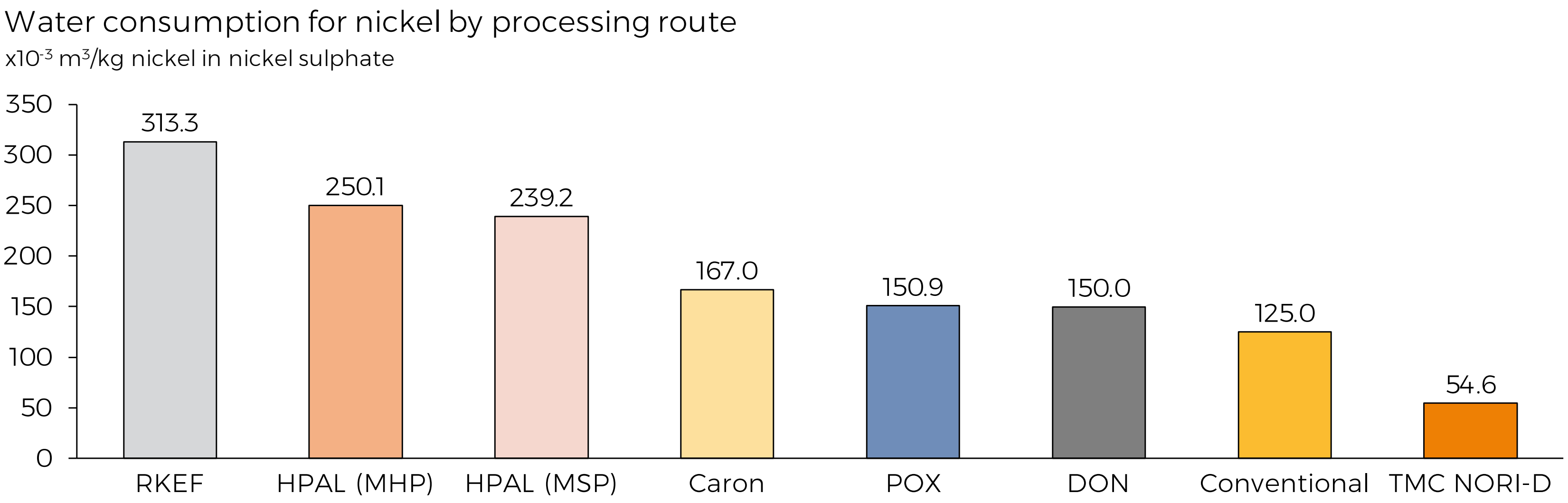
Freshwater eutrophication – Nickel in Nickel Sulphate comparison by route



Marine eutrophication – Nickel in Nickel Sulphate comparison by route



Water consumption – Nickel in Nickel Sulphate comparison by route



Overall results per midpoint impact category - 1 kg of Nickel in Nickel Sulphate

Impact category	**Unit**	**RKEF**	**Conventional**	**DON**	**HPAL (MHP)**	**HPAL (MSP)**	**Caron**	**POX**	**TMC NORI-D**
Global warming	kg CO_2 eq	101.96302	28.467983	29.206184	19.230109	13.873248	64.434107	7.9741725	6.1655693
Stratospheric ozone depletion	kg CFC11 eq	1.41E-05	2.71E-05	2.75E-05	3.10E-06	3.08E-06	1.73E-05	3.35E-06	7.33E-07
Ionizing radiation	kBq Co-60 eq	0.34167194	0.24753029	0.57079942	0.16703579	0.27260792	0.76121375	0.85223068	-0.0468078
Ozone formation, Human health	kg NOx eq	0.1678171	0.14592062	0.14695515	0.037631471	0.026050284	0.05037446	0.02252467	0.01278801
Fine particulate matter formation	kg PM2.5 eq	1.1875648	0.04288243	0.043137177	0.26181522	0.16042781	0.03173761	0.03948997	0.00922689
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.16885246	0.14804683	0.14913259	0.037886718	0.026303583	0.05275732	0.02289517	0.01278416
Terrestrial acidification	kg SO_2 eq	0.96193798	0.13159514	0.12946113	0.68704895	0.53247899	0.09460239	0.12475186	0.03087316
Freshwater eutrophication	kg P eq	0.09098444	0.076369381	0.075802279	0.009122215	0.005207313	0.0095108	0.00287315	0.00098393
Marine eutrophication	kg N eq	0.00551273	0.002297362	0.002262583	-0.00178026	-0.00125293	0.00012542	0.00018007	-0.0021456
Terrestrial ecotoxicity	kg 1,4-DCB	78.494714	59.20789	59.912684	235.4767	217.82653	70.083375	71.023416	-12.903241
Freshwater ecotoxicity	kg 1,4-DCB	2.791976	39.09554	39.084279	2.3437607	1.9242682	0.51712268	0.76135047	-0.1781432
Marine ecotoxicity	kg 1,4-DCB	3.8215862	48.54944	48.533593	3.1465615	2.5568831	0.71529666	0.99241586	-0.1749404
Human carcinogenic toxicity	kg 1,4-DCB	5.0349028	2.9743766	2.9426215	1.0102284	0.51774087	0.51014716	0.29158074	-0.002728
Human non-carcinogenic toxicity	kg 1,4-DCB	102.94334	389.16696	388.50703	57.389375	40.333431	11.02026	14.938914	-0.979332
Land use	m^2a crop eq	76.428943	64.886448	64.919871	46.820401	38.730376	48.069141	9.1525679	0.02912704
Mineral resource scarcity	kg Cu eq	3.584573	4.0620341	4.0626338	3.5290715	2.9317615	3.9467478	3.4243294	0.27882357
Fossil resource scarcity	kg oil eq	20.476639	6.4368286	6.6792072	2.2043699	1.9576204	21.209772	1.0865287	1.3384597
Water consumption	m^3	0.31331988	0.12542769	0.15002798	0.25008344	0.23917149	0.16674952	0.15085574	0.05456705

Overall results per endpoint impact category - 1 kg of Nickel in Nickel Sulphate

Damage category	**Unit**	**RKEF**	**Conventional**	**DON**	**HPAL (MHP)**	**HPAL (MSP)**	**Caron**	**POX**	**TMC NORI-D**
Human health	DALY	8.82×10^{-4}	1.52×10^{-4}	1.53×10^{-4}	1.99×10^{-4}	1.25×10^{-4}	8.43×10^{-5}	3.67×10^{-5}	1.14×10^{-5}
Ecosystems	species.yr	1.26×10^{-6}	7.88×10^{-7}	7.90×10^{-7}	6.34×10^{-7}	5.09×10^{-7}	6.43×10^{-7}	1.37×10^{-7}	2.69×10^{-8}
Resources	USD2013	3.23	1.84	1.99	1.32	1.21	10.36	1.05	0.37

Appendix 10

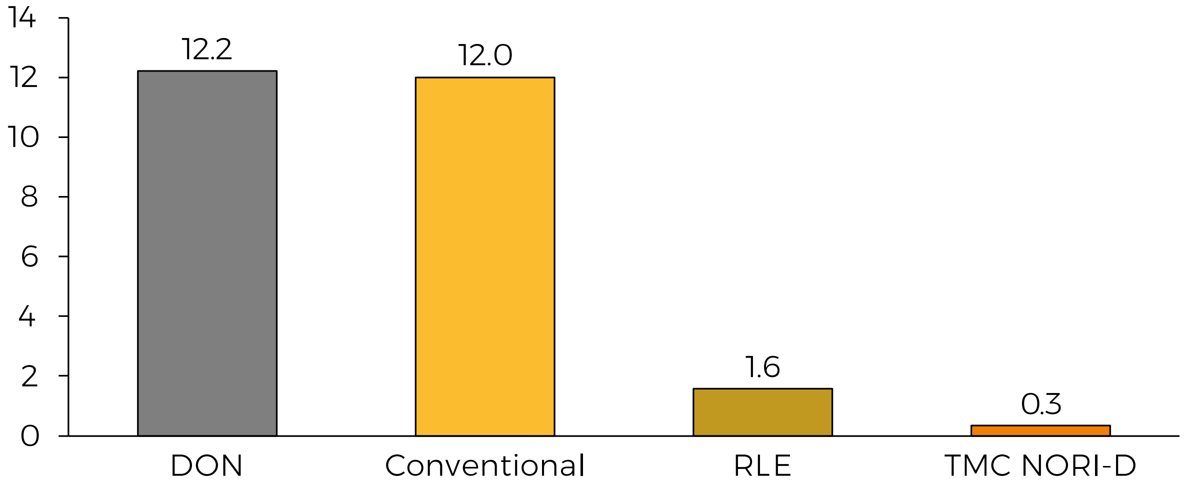
TMC NORI-D results versus land-based mining and processing

c) copper cathode comparison

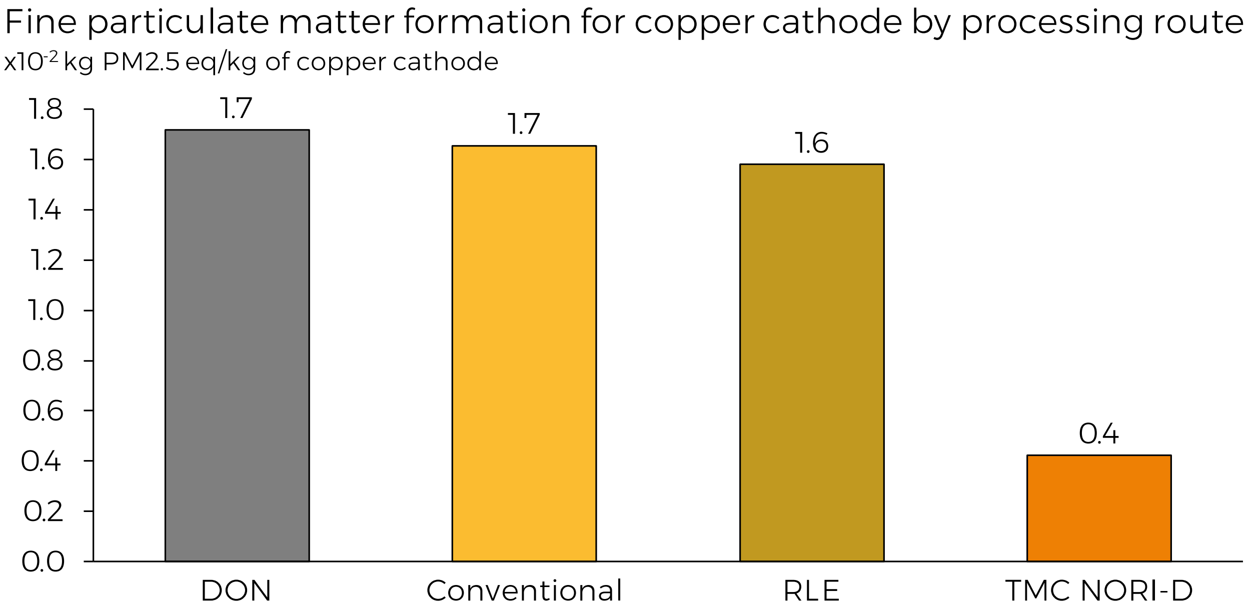
Ozone depletion – Copper cathode comparison by route

Stratospheric ozone depletion for copper cathode by processing route

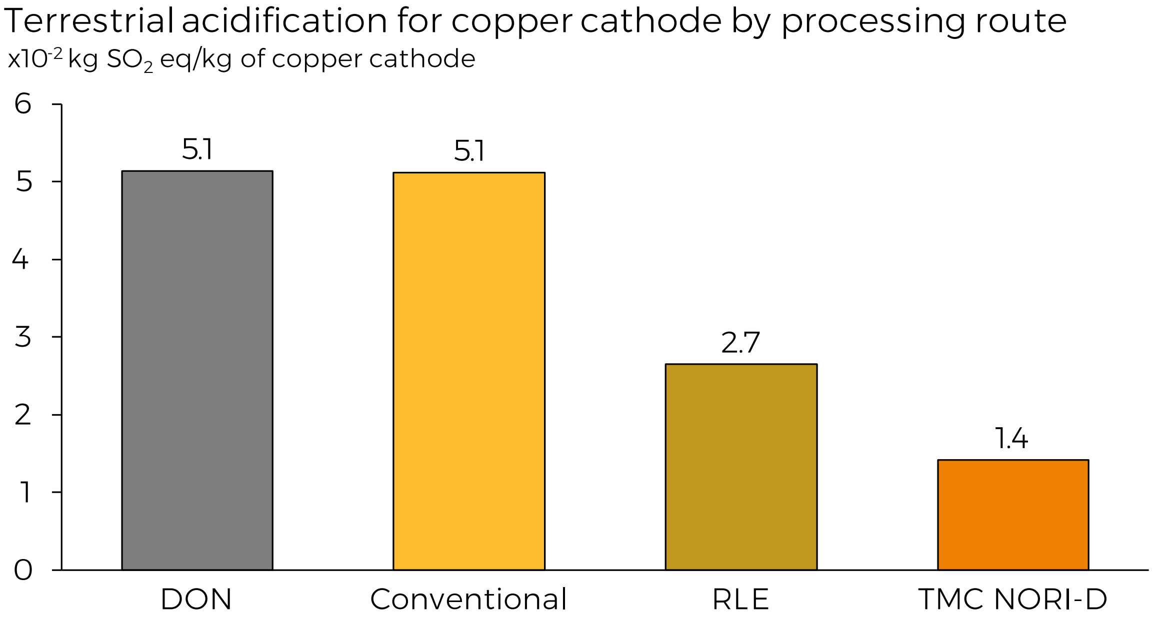
x10^{-6} kg CFC11 eq/kg of copper cathode



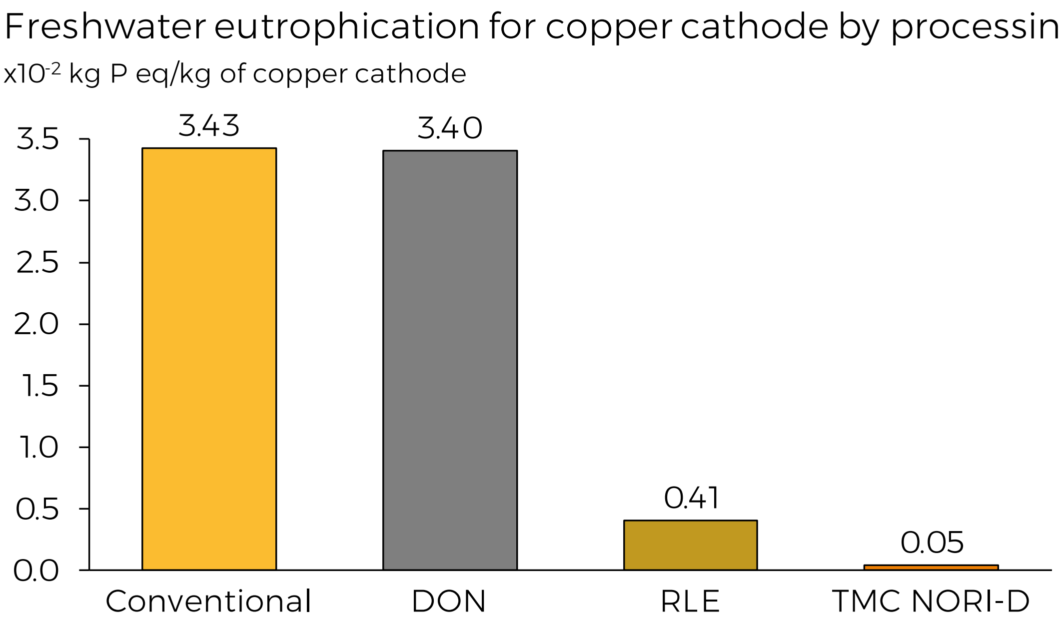
Fine particulate matter formation – Copper cathode comparison by route



Terrestrial acidification– Copper cathode comparison by route



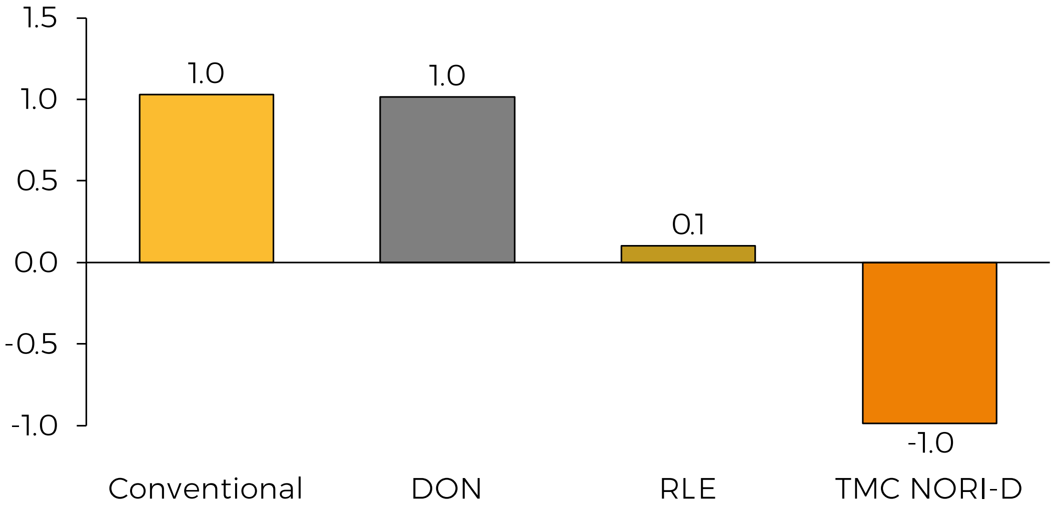
Freshwater eutrophication – Copper cathode comparison by route



Marine eutrophication – Copper cathode comparison by route

Marine eutrophication for copper cathode by processing route

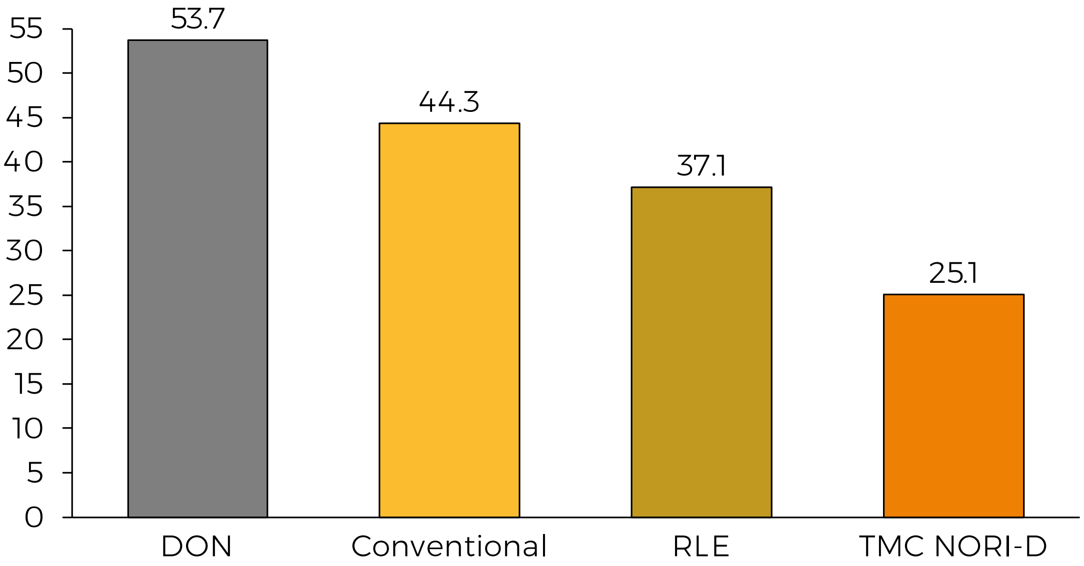
x10^{-3} kg N eq/kg of copper cathode



Water consumption – Copper cathode comparison by route

Water consumption for copper cathode by processing route

x10^{-3} m^3 eq/kg of copper cathode



Overall results per midpoint impact category - 1 kg of Copper cathode

Impact category	**Unit**	**Conventional**	**DON**	**RLE**	**TMC NORI-D**
Global warming	kg CO_2 eq	12.093324	12.746556	3.1884947	2.8360068
Stratospheric ozone depletion	kg CFC11 eq	1.20E-05	1.22E-05	1.58E-06	3.37E-07
Ionizing radiation	kBq Co-60 eq	0.095422747	0.13377604	0.05568442	-0.0215304
Ozone formation, Human health	kg NOx eq	0.062796801	0.064265764	0.02697525	0.00588216
Fine particulate matter formation	kg PM2.5 eq	0.01655342	0.01717839	0.0158266	0.00424414
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.063726238	0.06521753	0.02740538	0.00588039
Terrestrial acidification	kg SO_2 eq	0.051156626	0.051353536	0.02654177	0.01420088
Freshwater eutrophication	kg P eq	0.034252024	0.034038455	0.00408757	0.00045258
Marine eutrophication	kg N eq	0.001028433	0.001013534	0.00010203	-0.0009869
Terrestrial ecotoxicity	kg 1,4-DCB	5.8667672	6.2739324	26.516555	-5.9351664
Freshwater ecotoxicity	kg 1,4-DCB	17.52704	17.523789	3.1716617	-0.0819414
Marine ecotoxicity	kg 1,4-DCB	21.753101	21.748614	3.9598013	-0.0804682
Human carcinogenic toxicity	kg 1,4-DCB	1.2946478	1.2893029	0.16630185	-0.0012548
Human non-carcinogenic toxicity	kg 1,4-DCB	172.68273	172.49813	34.471043	-0.4504681
Land use	m^2a crop eq	29.372345	29.383568	0.80373292	0.01339771
Mineral resource scarcity	kg Cu eq	1.8281062	1.8283382	1.9963127	0.12825183
Fossil resource scarcity	kg oil eq	2.7167488	2.8828669	0.8698058	0.61565781
Water consumption	m^3	0.044327611	0.0536898	0.03713317	0.02509947

Overall results per endpoint impact category - 1 kg of Copper cathode

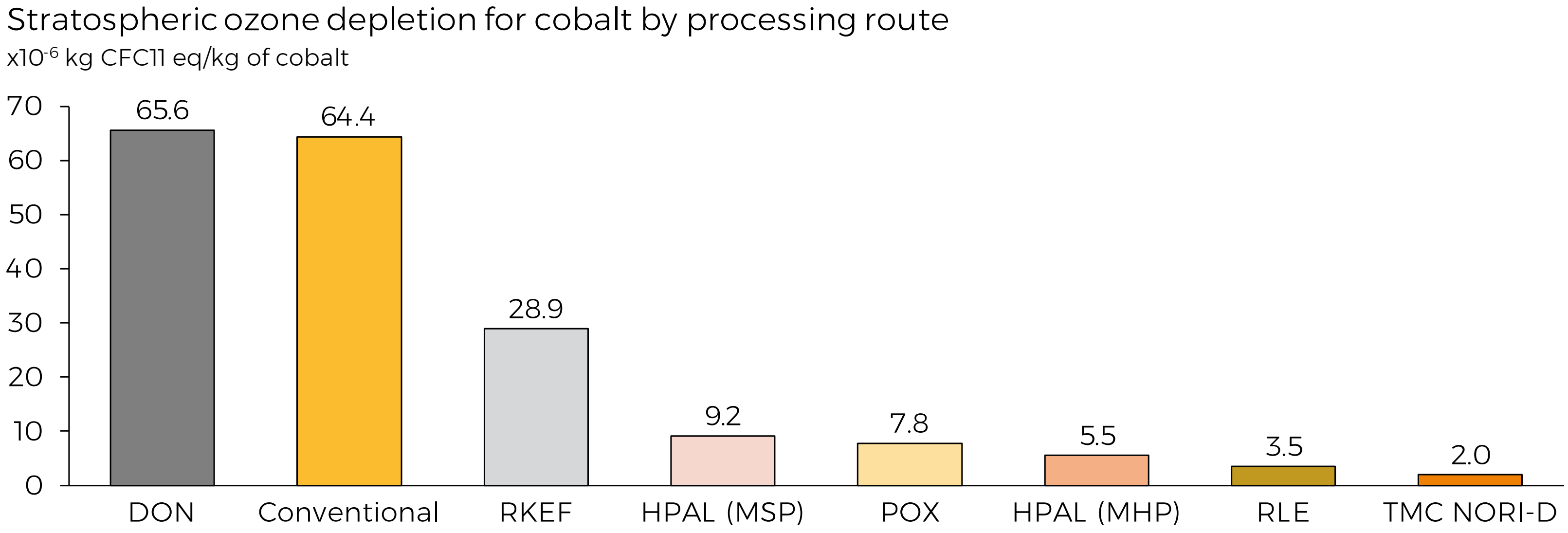
Damage category	**Unit**	**Conventional**	**DON process**	**RLE**	**TMC NORI-D**
Human health	DALY	6.55×10^{-5}	6.64×10^{-5}	2.14×10^{-5}	5.25×10^{-6}
Ecosystems	species.yr	3.51×10^{-7}	3.53×10^{-7}	2.56×10^{-8}	1.24×10^{-8}
Resources	USD2013	0.78	0.85	0.82	0.17

Appendix 11

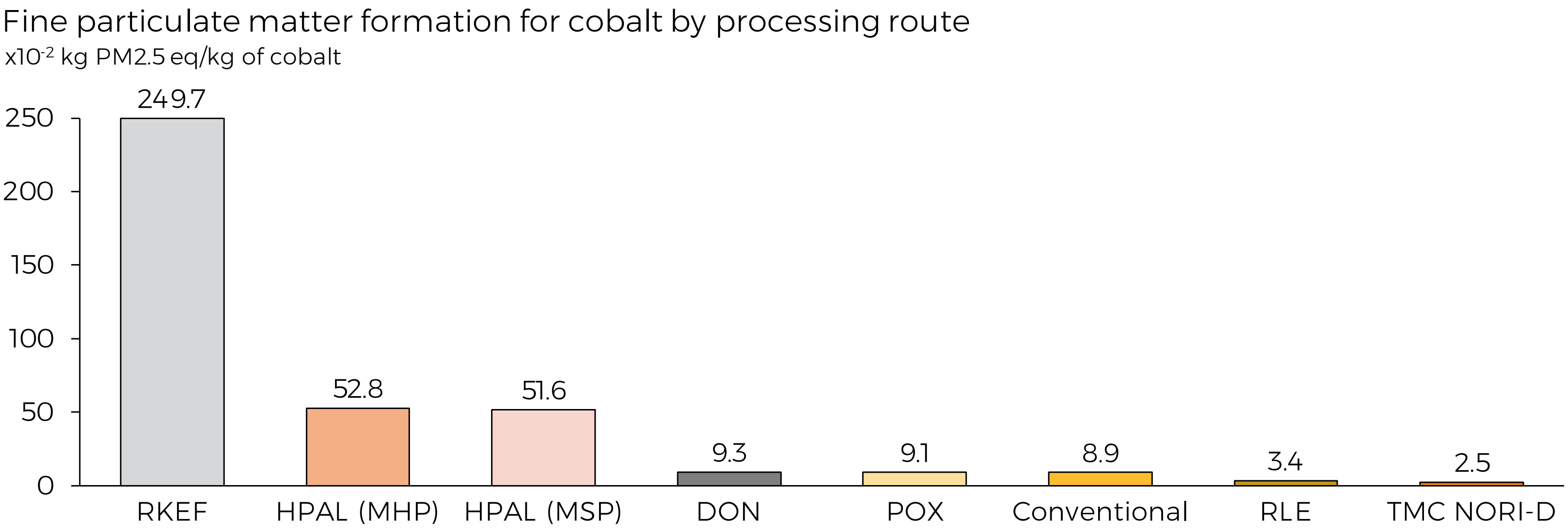
TMC NORI-D results versus land-based mining and processing

d) cobalt comparison

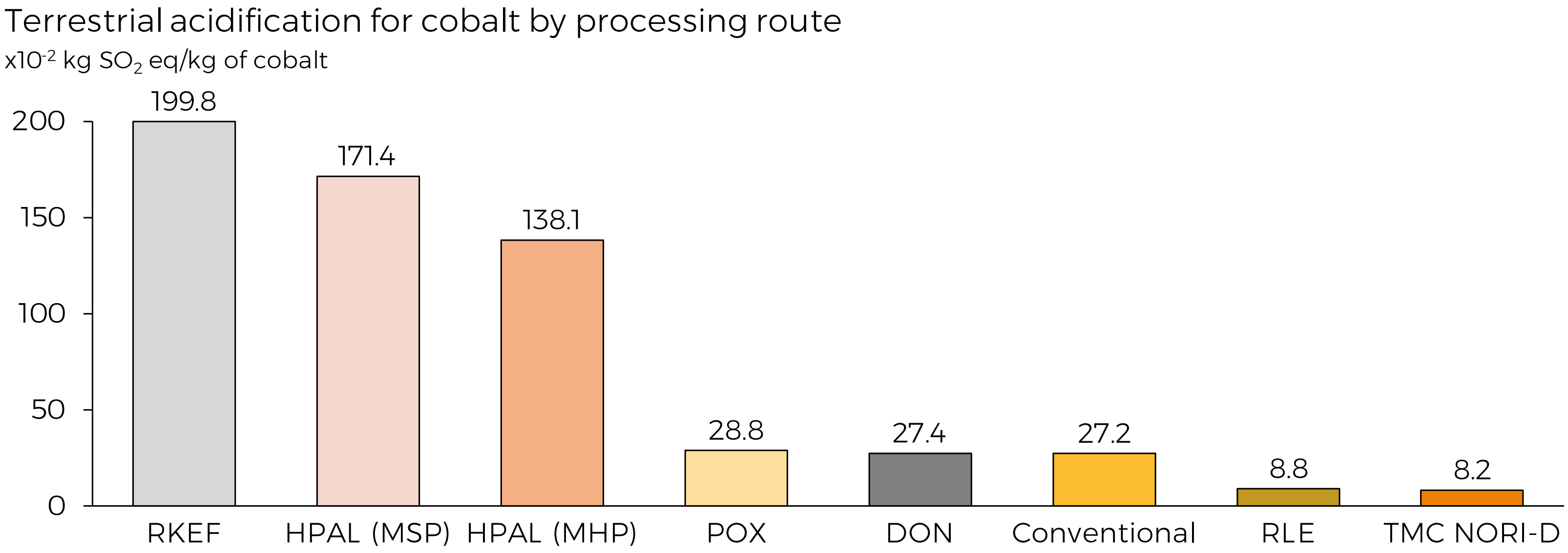
Ozone depletion – Cobalt comparison by route



Fine particulate matter formation – Cobalt comparison by route



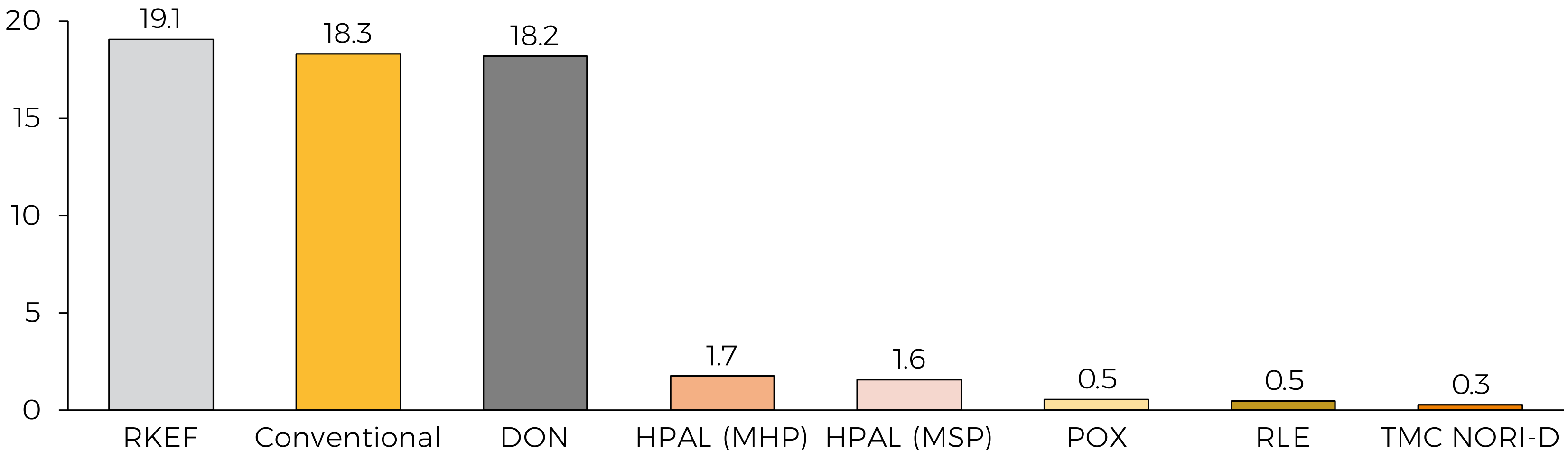
Terrestrial acidification– Cobalt comparison by route



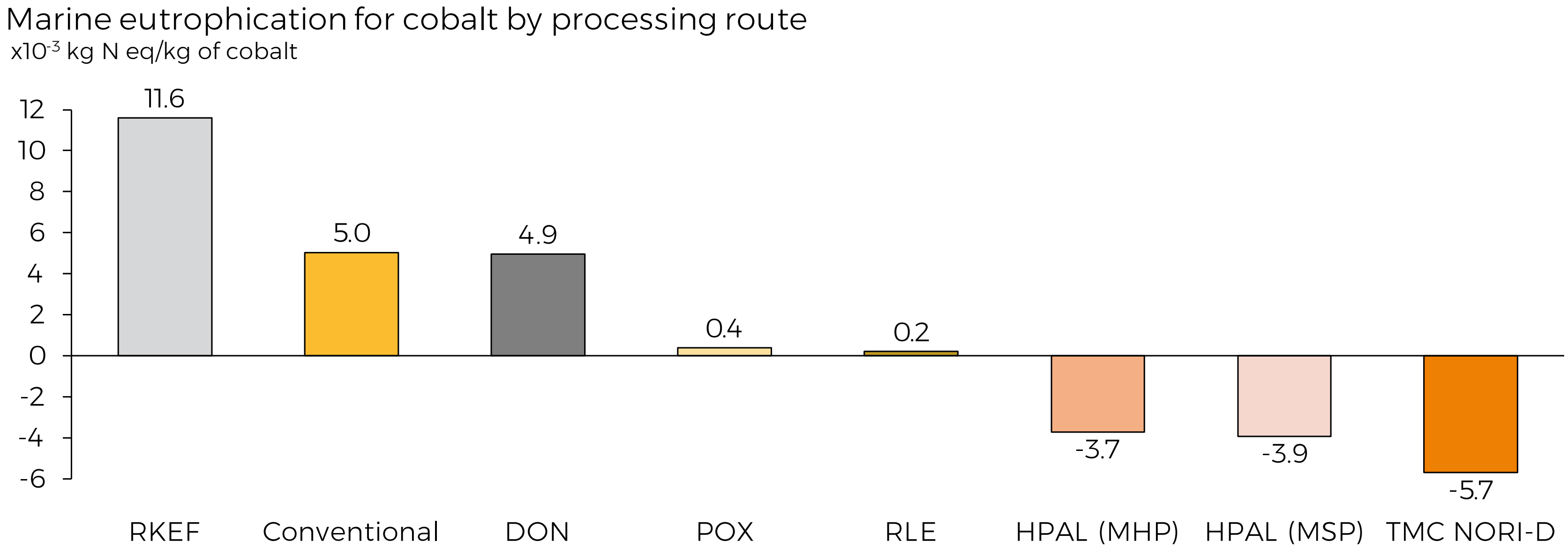
Freshwater eutrophication – Cobalt comparison by route

Freshwater eutrophication for cobalt by processing route

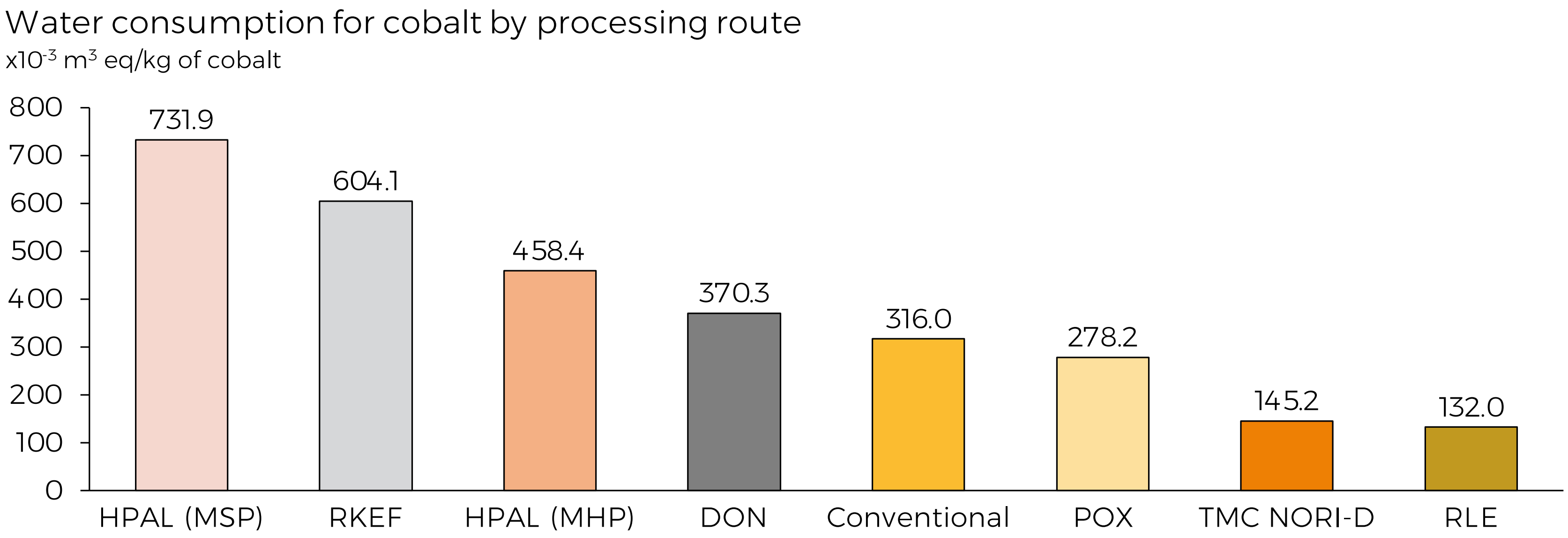
$\times 10^{-2}$ kg P eq/kg of cobalt



Marine eutrophication – Cobalt comparison by route



Water consumption – Cobalt comparison by route



Overall results per midpoint impact category – 1 kg of Cobalt

Impact category	**Unit**	**RKEF**	**Conventional**	**DON**	**HPAL (MHP)**	**HPAL (MSP)**	**POX**	**RLE**	**TMC NORI-D**
Global warming	kg CO_2 eq	212.01664	62.691495	66.502804	36.29398	43.04569	18.434082	10.409377	16.409917
Stratospheric ozone depletion	kg CFC11 eq	2.89E-05	6.44E-05	6.56E-05	5.51E-06	9.16E-06	7.80E-06	3.51E-06	1.95E-06
Ionizing radiation	kBq Co-60 eq	0.64843114	3.7032797	3.927059	0.272363	0.6948	1.7948043	0.21082623	-0.124581
Ozone formation, Human health	kg NOx eq	0.34485063	0.35054741	0.35911959	0.068043	0.078431	0.05240491	0.04470085	0.03403582
Fine particulate matter formation	kg PM2.5 eq	2.497162	0.088939925	0.092586537	0.527617	0.516231	0.09094898	0.03400077	0.02455775
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.34693258	0.35596023	0.36466272	0.068466	0.079117	0.05323943	0.04529692	0.03402556
Terrestrial acidification	kg SO_2 eq	1.9980201	0.27240859	0.27355919	1.381048	1.713872	0.2875149	0.08789627	0.0821702
Freshwater eutrophication	kg P eq	0.19067031	0.18306457	0.18181988	0.017279	0.015678	0.00548644	0.00462723	0.00261878
Marine eutrophication	kg N eq	0.011590391	0.005035142	0.004948259	-0.00372	-0.00393	0.00038941	0.00020359	-0.0057105
Terrestrial ecotoxicity	kg 1,4-DCB	71.586983	33.350347	35.725934	392.9051	606.6275	69.095219	130.07205	-34.342509
Freshwater ecotoxicity	kg 1,4-DCB	5.0492595	101.84598	101.82773	3.997444	5.363731	0.93379387	2.7085167	-0.4741354
Marine ecotoxicity	kg 1,4-DCB	6.9641678	126.34371	126.31841	5.396479	7.143862	1.2153711	3.4510582	-0.465611
Human carcinogenic toxicity	kg 1,4-DCB	10.40535	6.6878966	6.6567601	1.854348	1.496167	0.51139388	0.49278873	-0.0072607
Human non-carcinogenic toxicity	kg 1,4-DCB	200.76997	990.38771	989.31763	101.8608	114.0062	18.655033	39.535482	-2.6065324
Land use	m^2a crop eq	161.37751	171.56026	171.62692	96.29159	132.9181	23.56515	1.0532263	0.07752283
Mineral resource scarcity	kg Cu eq	7.5175314	10.667826	10.669253	7.210974	9.991431	8.7816714	1.2040634	0.74210043
Fossil resource scarcity	kg oil eq	42.442028	13.916855	14.886063	3.742679	5.43386	2.1636793	2.1112228	3.5623658
Water consumption	m^3	0.60406065	0.31568979	0.37031006	0.458436	0.731895	0.27817759	0.13179124	0.14523245

Overall results per endpoint impact category – 1 kg of Cobalt

Damage category	**Unit**	**RKEF**	**Conventional**	**DON**	**HPAL (MHP)**	**HPAL (MSP)**	**POX**	**RLE**	**TMC NORI-D**
Human health	DALY	1.85E-03	3.63E-04	3.69E-04	3.95E-04	3.96E-04	8.04E-05	4.20E-05	3.04E-05
Ecosystems	species.yr	2.63E-06	2.01E-06	2.02E-06	1.28E-06	1.70E-06	3.35E-07	6.82E-08	7.15E-08
Resources	USD2013	6.63	4.45	4.86	2.53	3.75	2.49	0.95	0.97

Appendix 12

Abbreviations

Abbreviations

CCZ – Clarion–Clipperton Zone

CFC – Chlorofluorocarbon

Co – Cobalt

CO_2 – Carbon dioxide

Co–60 – Cobalt–60

Cu – Copper

DALY – Disability Adjusted Life Year

dam^3 – Cubic decametre

DON – Direct Outokumpu Nickel Smelting Process

GHG – Greenhouse gas

Gt – Gigatonne

GWh – Gigawatt hours

GWP – Global Warming Potential

hm^3 – Cubic hectometre

HPAL – High Pressure Acid Leach

ISO – International Organisation for Standardisation

Kt – Kilotonne

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

m^2a/km^2a – area time

m^3 – cubic metre

MHP – Mixed Hydroxide Precipitate

Mn – Manganese

MSP – Mixed Sulphide Precipitate

Mt – Megatonne

Mtpa – Megatonnes per annum

N – Nitrogen

Ni – Nickel

NOx – Nitrogen oxides

p – parts

P – Phosphorus

PJ – Petajoule

PM2.5 – Particulate Matter with a diameter of 2.5 microns or less

PMN – Pollymetallic nodules

POX – Pressure Oxidation Process

RKEF – Rotary Kiln-Electric Furnace

RLE – Roasters, leaching and electrowinning

SO_2 – Sulphur dioxide

SOx – Sulphur oxides

t – metric tonne

TMC – The Metals Company

CRITICAL REVIEW STATEMENT:

The Metals Company

Life Cycle Assessment for the Nori D Deep Sea Mining Project and Land Based Route Comparisons

Undertaken by Benchmark Mineral Intelligence

An independent critical review has been undertaken of the Benchmark Mineral Intelligence LCA study of The Metals Company's deep sea mining operations. The study investigates the potential environmental impacts of producing manganese silicate, matte, nickel sulphate, cobalt sulphate and copper cathode material from seabed collection of polymetallic nodules.

The report is believed to represent, on the basis of the available data, a fair and reasonable identification of the potential impacts related to the products under study. The report has been prepared according to the principles of the LCA standards ISO 14040:2006/AMD 1:2020 and ISO 14044:2006/AMD 2:2020, taking into account the assumptions and limitations highlighted in the report.

Within the limits of the review, the reviewer agrees with the report's findings and conclusions. The review finds that the work has been carried out with expertise and attention to detail. The data used, data quality and data applicability are accurately described in the LCA report. As far as the review can determine, environmental impact calculations have been carried out accurately. The system boundaries, allocation, and processes that have been included and excluded, are considered appropriate. Allocation is required due to the co-processing of the mixed metal content of the nodules, and this allocation leads to uncertainties, but the allocation is believed to have been expertly applied to produce the most robust possible results. There is also uncertainty in the results for conventional land-based mining, due to lack of detailed data from land-based producers, and also due to the variability of mining systems around the world. These uncertainties in both systems lead to uncertainties in the comparison between the two systems. Therefore, site specific data should be used in future comparisons for precise conclusions. These issues are considered to be reported in an accurate and balanced manner in the LCA report's conclusions.

In summary, the LCA study is considered to be diligently conducted and appropriately reported, and the results and conclusions are judged to be sound.

Gary Parker

Gary Parker
Director
Sustainability in Metrics
9 December 2022