LIFE CYCLE ASSESSMENT OF PRODUCTS FROM THE NORI-D POLYMETALLIC NODULES PROJECT

Prepared for THE METALS COMPANY
26th November 2024

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Our Statement

Information contained in this report has been compiled and computed from sources believed to be credible. Application of the data is strictly at the discretion and the responsibility of the reader. Minviro is not liable for any loss or damage arising from the use of the information in this document.

Life cycle assessment (LCA) is an environmental accounting method with an inherent level of uncertainty, and it should not be seen as having the same level of precision as financial accounting. Life cycle assessment requires a very large amount of data, particularly to calculate all the inputs and outputs for every step.

Primary data are measured at the clients processing site or pilot plant and collected. Databases are often used for secondary data since it is impractical to collect all the necessary data from the original sources. The report does not claim to be exhaustive, nor does it claim to cover all relevant products. While steps have been taken to ensure accuracy, the listing or featuring of a particular product or company does not constitute an endorsement by Minviro.

The Metals Company (TMC) commissioned Minviro Ltd as an LCA practitioner in August 2023 to conduct an LCA quantifying the environmental impacts associated with the production of $MnSiO_3$, Ni-Cu-Co matte, copper cathode, nickel sulphate hexahydrate ($NiSO_4 \cdot 6H_2O$), and cobalt sulfate heptahydrate ($CoSO_4 \cdot 7H_2O$) from NORI-D Project polymetallic nodules. The results of this study are for internal and external use and are intended to be communicated to the public.

Table 1: Document Details.

Document Details	
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Table 2: Revision Details.

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2.1	8th November 2024	Keno Ignace and Lorraine Amponsah	Quentin Dehaine, Joris Šimaitis, and Irdanto Saputra Las	Various comments.
2.2	26th November 2024	Keno Ignace	Quentin Dehaine, Joris Šimaitis, and Irdanto Saputra Las	Editorial comments for client compliance.

Executive Summary

Introduction, Goal, and Scope of the Study

A significant resource of polymetallic nodules, rich in nickel, manganese, cobalt, and copper, is located on the seafloor of the Clarion-Clipperton Zone (CCZ) in the northeast Pacific Ocean. The Metals Company ("TMC") has identified an opportunity to recover these metals to meet the growing demand for infrastructure development (e.g., silico-manganese for the steel industry) and energy transition technologies (nickel, copper, and cobalt).

Unlike terrestrial mining which requires the removal of overburden and waste rock, polymetallic nodules lie unattached on the seafloor, therefore their collection eliminates the need for extensive land disturbance, thus minimising waste management. TMC aims to further minimise waste generation by producing useful products, thereby reducing the need for large-scale waste or tailings facilities.

TMC commissioned life cycle assessment (LCA) practitioner Minviro Ltd ("Minviro") in August 2023 for the completion of a study which aims to quantify the environmental impacts associated with the production of $MnSiO_3$, Ni-Cu-Co matte, copper cathode, nickel sulphate hexahydrate ($NiSO_4 \cdot 6H_2O$), and cobalt sulfate heptahydrate ($CoSO_4 \cdot 7H_2O$) from NORI-D Project polymetallic nodules.

The goals of the study are stated in **Section 3**. LCA is the most comprehensive and recognized tool for measuring the environmental performance of products and processes over an array of environmental impact categories, taking a holistic approach to include environmental impacts upstream and downstream of conventional organisational boundaries depending on the scope of the study. However, it is important to note that this study does not assess environmental impacts on the seafloor or biodiversity impacts as current life cycle assessment (LCA) methodology lacks a framework to accurately quantify these effects. This represents a limitation of the study.

The primary goal of this LCA is to provide TMC with insights to guide environmental impact reduction strategies and enhance the environmental impact profile of the NORI-D project. The target audience includes investors, customers, and those interested in deep-sea mining. The results are intended for public communication.

Table 3 summarises the distinguishing features of this study, contrasting it with a previous LCA conducted on the NORI-D project by another practitioner.

Table 3: Comparison of Key Characteristics and System Specifications Between TMC's Current NORI-D LCA conducted by Minviro and the Benchmark NORI-D LCA.

Parameter	PEA NORI-D LCA - Benchmark[46] report*	PEA PFS NORI-D LCA - Minviro report**
Quantity of polymetallic nodules processed annually	12.5 megatonnes (wet) /yr	12 megatonnes (wet) / yr
Core unit processes and base-case location assumptions	1. Offshore collection of polymetallic nodules in NORI-D contact area, CCZ. 2. Pyrometallurgy (production of $MnSiO_3$) in Texas 3. Hydrometallurgy (production of copper cathode, $NiSO_4{\cdot}6H_2O$ and $CoSO_4{\cdot}7H_2O$) in Texas	1. Offshore collection of polymetallic nodules in NORI-D contact area, CCZ. 2. Pyrometallurgy (production of $MnSiO_3$) in Indonesia or Japan using the national grid mix. 3. Hydrometallurgy (production of copper cathode, $NiSO_4{\cdot}6H_2O$ and $CoSO_4{\cdot}7H_2O$) in South Korea on the national grid mix.
Co-products	$MnSiO_3$, $CoSO_4{\cdot}7H_2O$, $NiSO_4{\cdot}6H_2O$, copper cathode	$MnSiO_3$, $CoSO_4{\cdot}7H_2O$, $NiSO_4{\cdot}6H_2O$, copper cathode
Other products (by-products)	Ammonium sulfate (assumed to be a substitute for globally produced ammonium sulfate used in the Chemicals and Agriculture Industry) and converter slag (assumed to be used as an aggregate material in road construction)	Ammonium sulfate (assumed to be a substitute for globally produced ammonium sulfate used in the Chemicals and Agriculture Industry) and converter slag (assumed to be used as an aggregate material in road construction)
Functional units	1kg of $MnSiO_3$ 1kg of Ni-Cu-Co matte 1kg of Ni in $NiSO_4{\cdot}6H_2O$ 1kg of Co in $CoSO_4{\cdot}7H_2O$ 1kg of copper cathode	1kg of $MnSiO_3$ 1kg of Ni-Cu-Co matte*** 1kg of dry polymetallic nodules processed 1kg of Ni in $NiSO_4{\cdot}6H_2O$ 1kg of Co in $CoSO_4{\cdot}7H_2O$ 1kg of copper cathode
Foreground data sources	Project scenario and data based from NORI-D Project Initial Assessment (March 2021)[47]****	Project scenario based from TMC's internal NORI-D Project PFS (November 2024)**** and onshore technical data was taken from SK-1300 compliant NORI-D Project Initial Assessment (March 2021).[47]
Background data source	Ecoinvent 3.8	Ecoinvent 3.10
Energy Sources	Pyrometallurgy: Texas - 100% wind	Pyrometallurgy: Indonesia or Japan - Grid (base case)

	(base case) Hydrometallurgy: Texas - 100% wind (base case)	Hydrometallurgy: South Korea - Grid (base case)
Energy Sources Breakdown	**Texas: 100% wind energy**	**Indonesian grid mix (2023)** - 65% lignite, 22% nat. gas, 7% hydro, 6% other. **Japanese grid mix (2023) -** 33.4% coal, 45% natural gas, 8% hydro, 4.6% nuclear, 2% petroleum, 2% woodchips, 5.4% other. **South Korean grid mix (2023) -** 33.4% coal, 29.1% nat. gas, 27.6% nuclear, 4.5% solar, 1.1% hydro, 1.0% oil, 3.3% other.
Energy Source Breakdown (Scenario Analysis)	**N/A**	**Indonesia 25% solar, 75% coal** **Indonesia 100% hydro** **Japan 100% Nuclear** **South Korea 100% Nuclear**
*** When the functional unit of 1kg Ni-Cu-Co matte is used, note that the environmental impacts associated with downstream processes are excluded - namely the transport and hydrometallurgical processing of the Ni-Cu-Co matte***. **** TMC's internal NORI-D Project PFS is not publicly available at the time of release of this study.		

A cradle-to-gate system boundary has been adopted – a diagram showcasing the product system evaluated is presented below in **Figure 1**. The 'cradle' is the collection of the polymetallic nodules where the impact of producing and burning the marine fuel oil used in the process is quantified. The polymetallic nodules are then transported to onshore operations in various locations where they are first processed in a pyrometallurgical circuit.

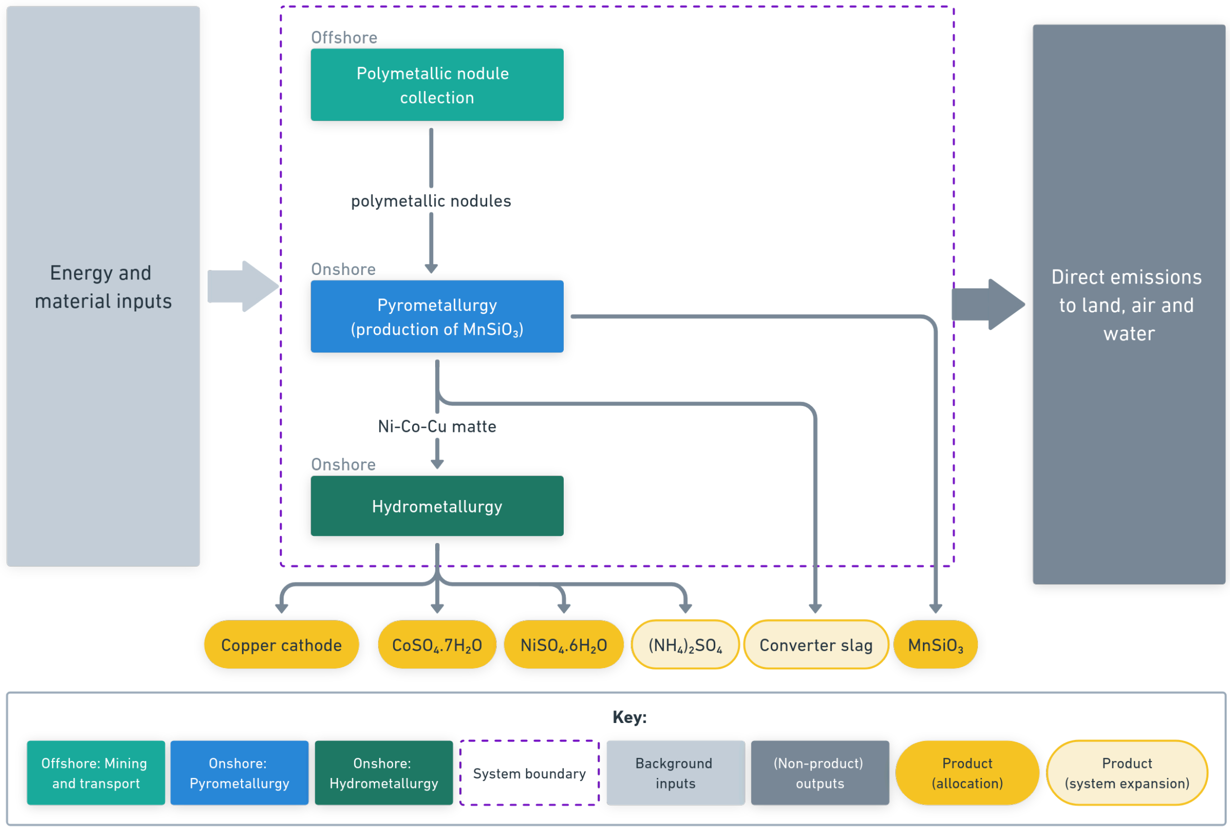

Figure 1: System Boundary Applied to the Life Cycle Assessment Study.

The system boundary includes the production of $MnSiO_3$ which is prepared for distribution but excludes downstream processing (e.g. via an additional pyrometallurgical process). The Ni-Cu-Co matte produced is transported to South Korea where it is further refined in a hydrometallurgical circuit to produce copper cathode, $NiSO_4{\cdot}6H_2O$ and $CoSO_4{\cdot}7H_2O$.

Note that biodiversity impacts on the seafloor from the nodule collection process were not quantified as LCA's currently lack any methodology around adequately quantifying these impacts. This should be considered a limitation of this study. Sensitivity analysis was conducted to assess the potential impact of various low-carbon and renewable electricity sources that TMC may adopt in the future. Additionally, the analysis examined the effects of transitioning from coal to natural gas for heating. Further analysis explored allocation methodologies, comparing economic allocation based on a 10-year average market value [43,44], economic allocation using a forecasted 10-year average market value[45], and mass allocation.

Methodology

TMC's processes were modelled using foreground data from their NORDI-D project (November 2024) and offshore data from SK-1300 compliant NORI-D Initial Assessment (March 2021).[47] The background data was sourced from ecoinvent database 3.10 and the life cycle impact assessment (LCIA) methodology applied was Environmental Footprint (3.1) across all impact categories (table 4). This approach satisfied the objectives of the study by providing the environmental impacts associated with the production of $MnSiO_3$, Ni-Cu-Co matte, copper cathode, $NiSO_4 \cdot 6H_2O$, and $CoSO_4 \cdot 7H_2O$, across the full range of environmental impact categories quantified in this assessment. Some proxy data-points were used for reagents, creating associated limitations to the study. It should be well noted this study does not measure the environmental impacts on the seafloor due to polymetallic nodule collection, as the life cycle assessment methodology currently lacks a framework for adequately quantifying these impacts.

Please note that the LCA methodology has certain limitations. Just as it does not fully capture impacts on biodiversity and terrestrial ecosystems from land-based mining, this study does not quantify environmental effects on the seafloor or deep-sea ecosystems. This limitation should be kept in mind when interpreting the study's findings. A full data quality assessment can be found in **Section 5.3**.

A comprehensive assessment was conducted across the full spectrum of EF impact categories. **Table 5 and 6** presents the key results from the study, focusing on the base-case scenarios for the production of $MnSiO_3$, Ni-Cu-Co matte, copper cathode, $NiSO_4 \cdot 6H_2O$, $CoSO_4 \cdot 7H_2O$, and the impacts associated with collecting and processing the dry nodules.

Table 4: Definitions of all environmental impact categories assessed in this study.

Term	Definition
Climate change	Increase in the average global temperature resulting from greenhouse gas emissions (GHG). Units are in total radiative forcing as global warming potential – GWP100 (kg CO2 eq).
Freshwater + terrestrial acidification	Acidification from air, water, and soil emissions (primarily sulphur compounds) mainly due to combustion processes in electricity generation, heating, and transport. Units are in accumulated exceedance – AE (mol H+ eq).
Aquatic freshwater eutrophication	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilisers, combustion, sewage systems. Units are in fraction of nutrients reaching the freshwater end compartment (kg P eq).
Terrestrial eutrophication	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilisers, combustion, sewage systems. Units are in Accumulated Exceedance – AE (mol N eq).
Freshwater ecotoxicity	Impact of toxic substances on freshwater ecosystems. Units are in the Comparative Toxic Unit for ecosystems (CTUe).
Aquatic marine eutrophication	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilisers, combustion, sewage systems. Units are in fraction of nutrients reaching marine end compartment (kg N eq).
Ionising radiation, human health	Impact of exposure to ionising radiations on human health. Units are in Human exposure efficiency relative to U-235 (kBq U-235 eq).
Photochemical ozone formation	Potential of harmful tropospheric ozone formation (“summer smog”) from air emissions. Units are in tropospheric ozone concentration increase (kg NMVOC eq).
Human toxicity, cancer effects - carcinogenic	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured. Units are in Comparative Toxic Unit for humans (CTUh).
Human toxicity, non-cancer effects - non-carcinogenic	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured. Units are in Comparative Toxic Unit for humans (CTUh).
Respiratory	Impact on human health caused by particulate matter emissions and its precursors (e. g. sulphur and nitrogen oxides). Units are in Impact on human health (disease incidence).
Ozone depletion	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation. Units are in Ozone Depletion Potential – ODP (kg CFC-11 eq).
Resource use, minerals and metals depletion	Depletion of non-renewable resources and deprivation for future generations. Units are in abiotic resource depletion – ADP ultimate reserves (kg Sb eq).
Resource use, fossil fuel depletion	Depletion of non-renewable resources and deprivation for future generations. Units are in abiotic resource depletion, fossil fuels – ADP-fossil (MJ).
Water	Assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived. Dimensionless, expressed as m3-world eq./m3
Land use	Transformation and occupation use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability. Units are based on soil quality index, representing the aggregated impact of land use on: biotic production; erosion resistance; mechanical filtration; groundwater replenishment (dimensionless – pt).

Table 5: Summary of LCA Results Obtained for the Base-case Scenarios, when Pyrometallurgy Occurs in Either Indonesia or Japan for the Matte, and MnSiO3 products, and for the Collection and Processing of the Dry Nodules.

Impact Category	Units	Per kg dry nodules processed		Per kg Ni-Cu-Co matte		Per kg Mn in $MnSiO_3$	
		Indonesia	Japan	Indonesia	Japan	Indonesia	Japan
Climate Change	kg CO2-Eq	1.25E+00	1.05E+00	5.26E+00	4.77E+00	3.21E+00	2.55E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	9.86E-03	1.12E-02	4.52E-02	3.90E-02	2.57E-02	2.21E-02
Freshwater Eutrophication	kg P-Eq	1.13E-03	2.72E-03	4.08E-03	1.17E-03	3.13E-03	5.21E-04
Terrestrial Eutrophication	mol N-Eq	1.26E-02	1.19E-02	5.82E-02	4.32E-02	3.36E-02	2.38E-02
Freshwater Ecotoxicity	CTU	-2.91E+00	-4.02E+00	1.28E+01	8.51E+00	7.65E+00	4.28E+00
Marine Eutrophication	kg N-Eq	1.33E-03	3.33E-03	6.09E-03	4.12E-03	3.69E-03	2.24E-03
Ionising Radiation	kg U235-Eq	1.26E-02	3.70E-02	1.09E-02	3.15E-02	6.67E-03	6.45E-02
Photochemical Ozone	kg NMVOC	4.05E-03	5.75E-03	1.76E-02	1.37E-02	1.07E-02	8.24E-03
Carcinogenic	CTUh	5.58E-10	2.48E-03	4.82E-09	4.93E-09	2.14E-09	2.73E-09
Non-Carcinogenic	CTUh	8.73E-09	2.48E-03	3.68E-08	2.37E-08	2.51E-08	1.41E-08
Respiratory	disease i.	1.04E-07	2.48E-03	4.02E-07	2.91E-07	2.89E-07	1.84E-07
Ozone Depletion	kg CFC-11	6.37E-09	2.48E-03	2.03E-08	2.70E-08	1.73E-08	2.55E-08
Minerals + Metals	kg Sb-Eq	-5.57E-06	2.47E-03	9.86E-07	9.52E-07	5.55E-07	6.66E-07
Fossils	MJ	1.33E+01	1.19E+01	5.35E+01	4.19E+01	3.39E+01	2.90E+01
Water	m3 world eq	1.13E-01	6.84E-02	3.85E-01	1.28E-01	2.88E-01	1.42E-01
Land	points	2.26E-01	2.27E-01	4.74E-03	3.42E-04	4.25E-03	2.02E-04

Table 6: Summary of LCA Results Obtained for the Base-case Scenarios, when Pyrometallurgy Occurs in Either Indonesia or Japan for the Ni, CO, and Cu products.

Impact Category	Units	Per kg Ni in $NiSO_4 \cdot 6H_2O$		Per kg Co in $CoSO_4 \cdot 7H_2O$		Per kg copper cathode	
		Indonesia	Japan	Indonesia	Japan	Indonesia	Japan
Climate Change	kg CO2-Eq	1.09E+01	1.01E+01	3.25E+01	3.02E+01	4.12E+00	3.79E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	6.99E-02	6.02E-02	2.08E-01	1.80E-01	2.90E-02	2.48E-02
Freshwater Eutrophication	kg P-Eq	6.91E-03	2.37E-03	2.06E-02	7.11E-03	2.87E-03	8.64E-04
Terrestrial Eutrophication	mol N-Eq	2.52E-01	2.28E-01	7.49E-01	6.79E-01	3.12E-02	2.08E-02
Freshwater Ecotoxicity	CTU	-2.59E+02	-2.66E+02	-7.64E+02	-7.84E+02	-1.16E+02	-1.19E+02
Marine Eutrophication	kg N-Eq	6.64E-03	3.56E-03	1.99E-02	1.08E-02	2.36E-03	1.00E-03
Ionising Radiation	kg U235-Eq	5.15E-01	5.47E-01	1.55E+00	1.64E+00	2.24E-01	2.38E-01
Photochemical Ozone	kg NMVOC	3.00E-02	2.38E-02	8.98E-02	7.14E-02	1.18E-02	9.09E-03
Carcinogenic	CTUh	-3.80E-09	-3.63E-09	-9.87E-09	-9.36E-09	-2.70E-09	-2.63E-09
Non-Carcinogenic	CTUh	3.58E-08	1.54E-08	1.09E-07	4.83E-08	1.30E-08	4.03E-09
Respiratory	disease i.	6.22E-07	4.49E-07	1.86E-06	1.34E-06	2.54E-07	1.77E-07
Ozone Depletion	kg CFC-11	1.37E-07	1.47E-07	4.08E-07	4.39E-07	2.56E-08	3.03E-08
Minerals + Metals	kg Sb-Eq	8.13E-02	8.13E-02	2.41E-01	2.41E-01	-1.25E-04	-1.25E-04
Fossils	MJ	1.30E+02	1.12E+02	3.88E+02	3.34E+02	4.96E+01	4.15E+01
Water	m3 world eq	1.15E+00	7.52E-01	3.48E+00	2.29E+00	-1.02E-02	-1.88E-01
Land	points	1.08E+01	1.08E+01	3.30E+01	3.30E+01	3.42E+00	3.42E+00

A full visual summary of the climate change impact for each functional unit (Mn in $MnSiO_3$, Ni-Cu-Co Matte, Cu cathode, Co in $CoSO_4 \cdot 7H_2O$, and Ni in $NiSO_4 \cdot 6H_2O$ and dry nodules processed) by processing location are shown in **Figures 2 and 3.**

A scenario analysis was also conducted to show how the base case climate change results for each functional unit would be impacted by possible future energy sources described in table 3. These results are shown in figures 4-9.

Climate Change Impact per functional unit in this study (base case – Indonesia)

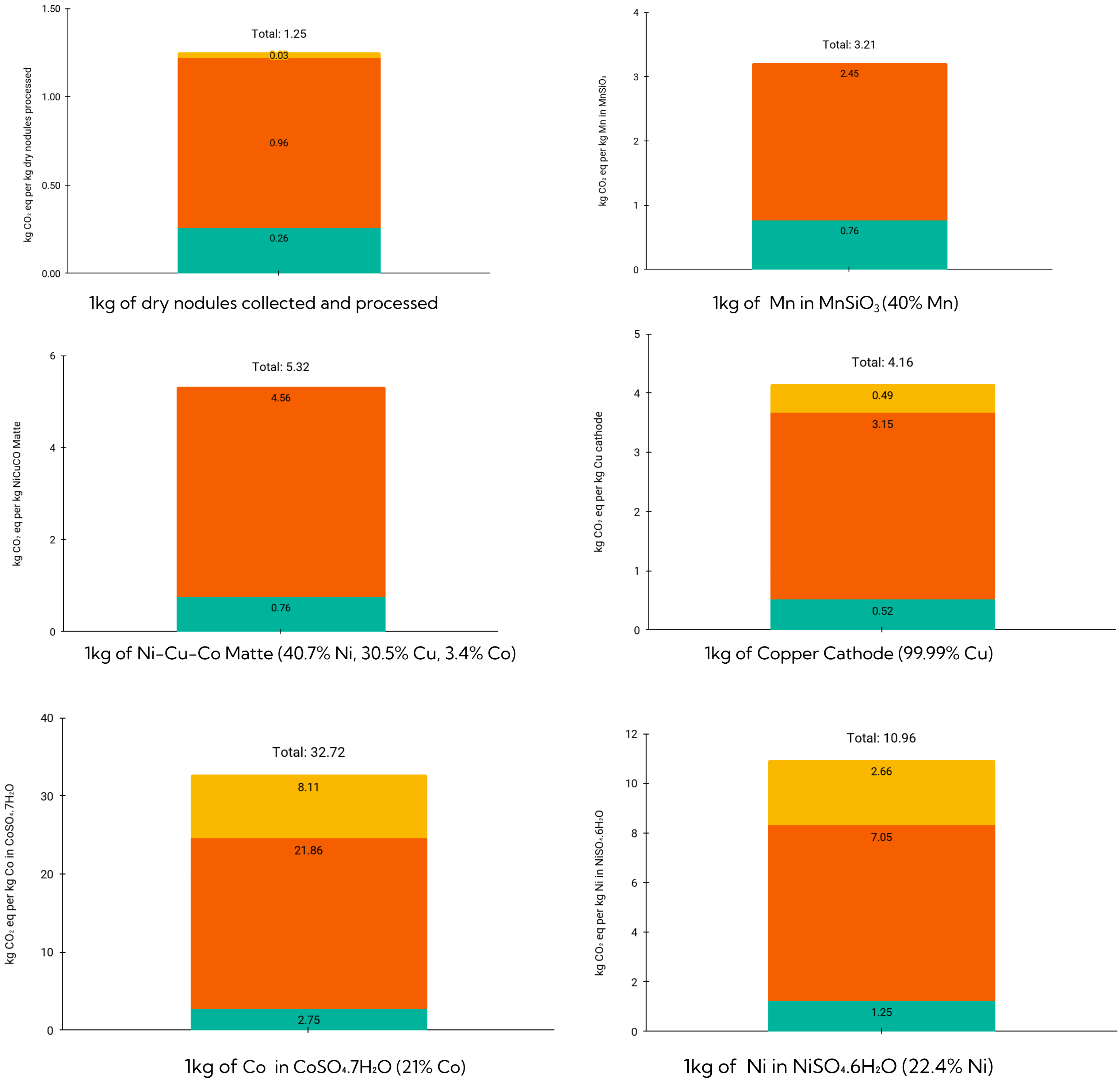

Figure 2: Climate Change Impact per kg of functional unit (base case - Indonesia) ***Green = offshore, orange = pyro , yellow = hydro***

Climate Change Impact per functional unit in this study (base case – Japan)

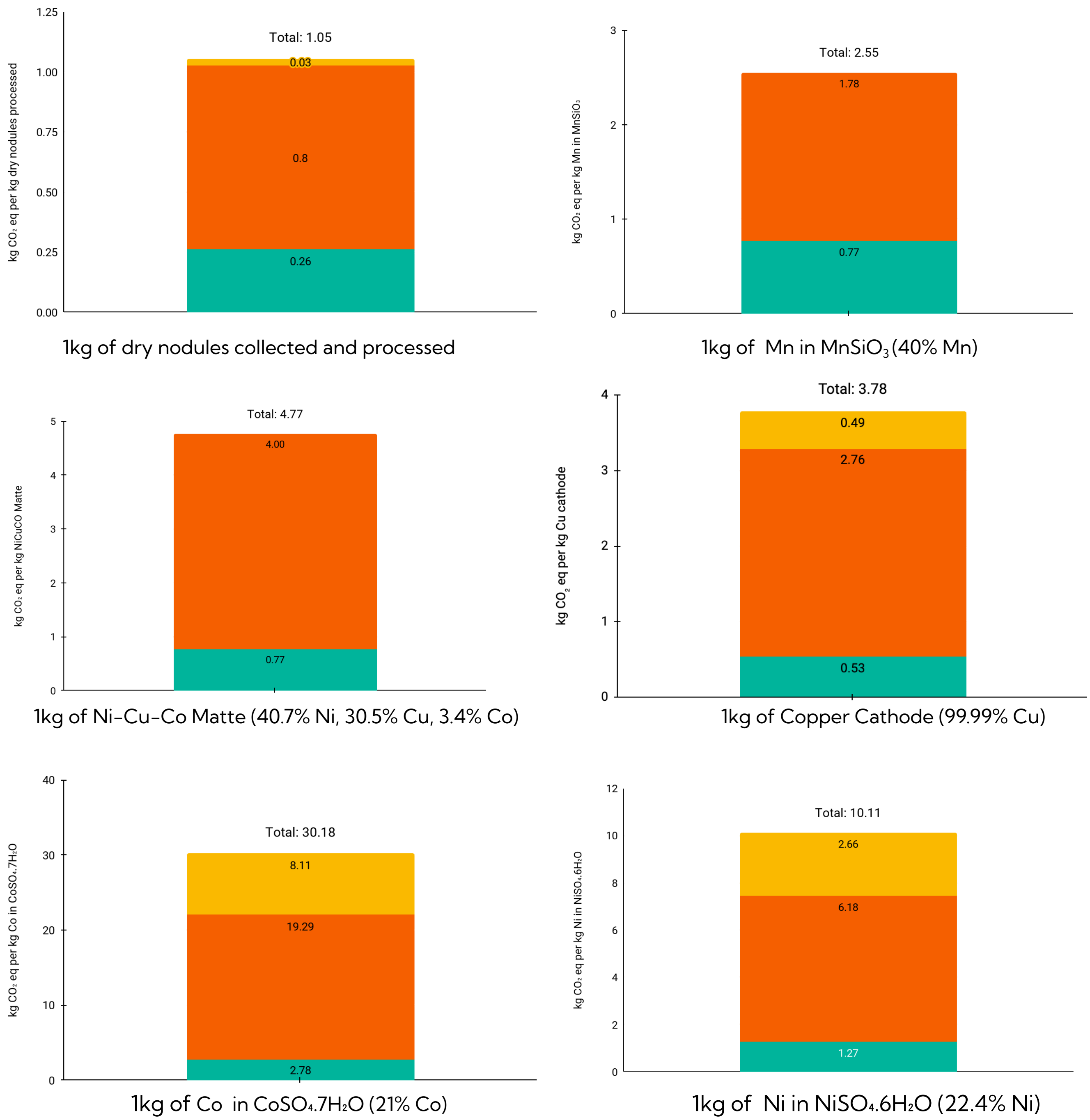

Figure 3: Climate Change Impact per kg of functional unit (base case - Japan) ***Green = offshore, orange = pyro , yellow = hydro***

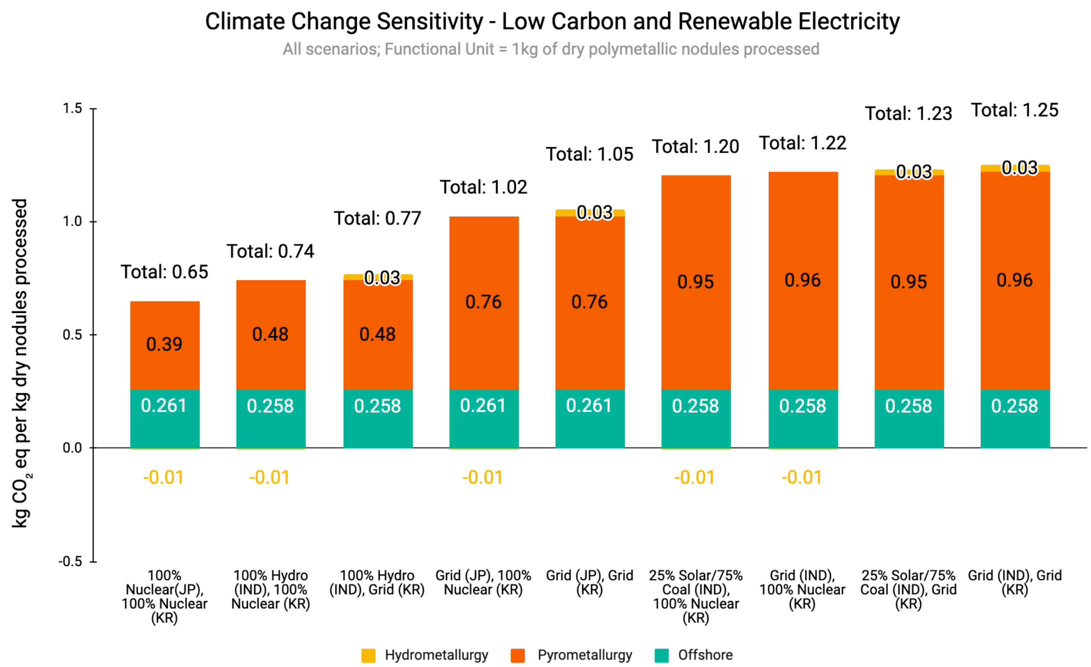

Figure 4: Sensitivity Analysis on the Variation in Global Warming Potential Impacts of processing the dry polymetallic nodules with the Application of Various Low Carbon and Renewable Electricity Mixes.

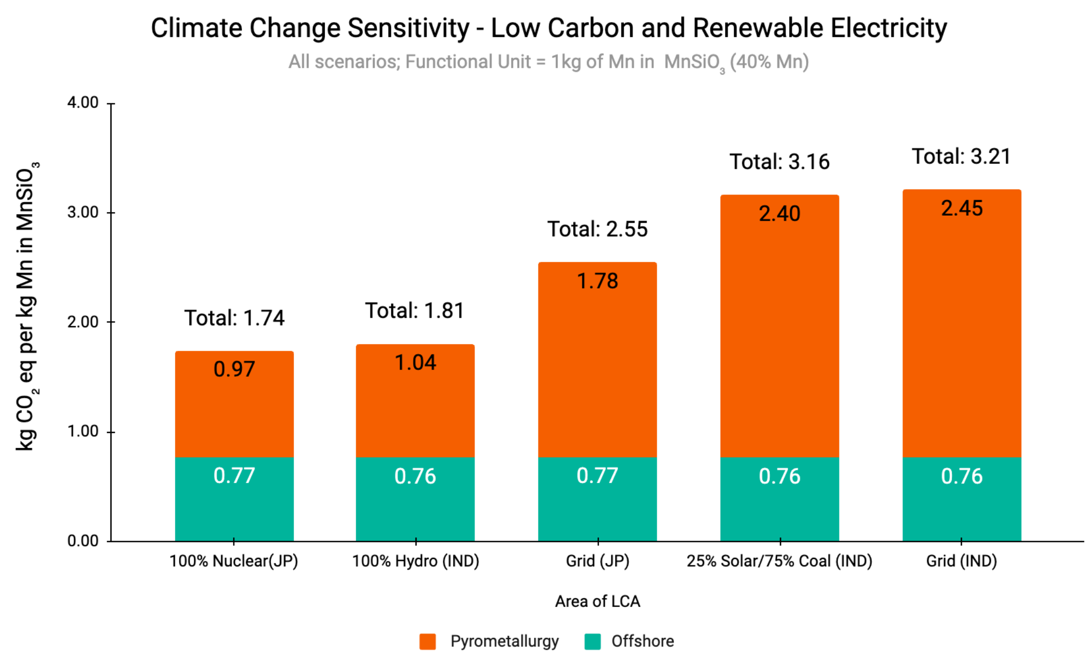

Figure 5: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for the production of $MnSiO_3$ with the Application of Various Low Carbon and Renewable Electricity Mixes.:

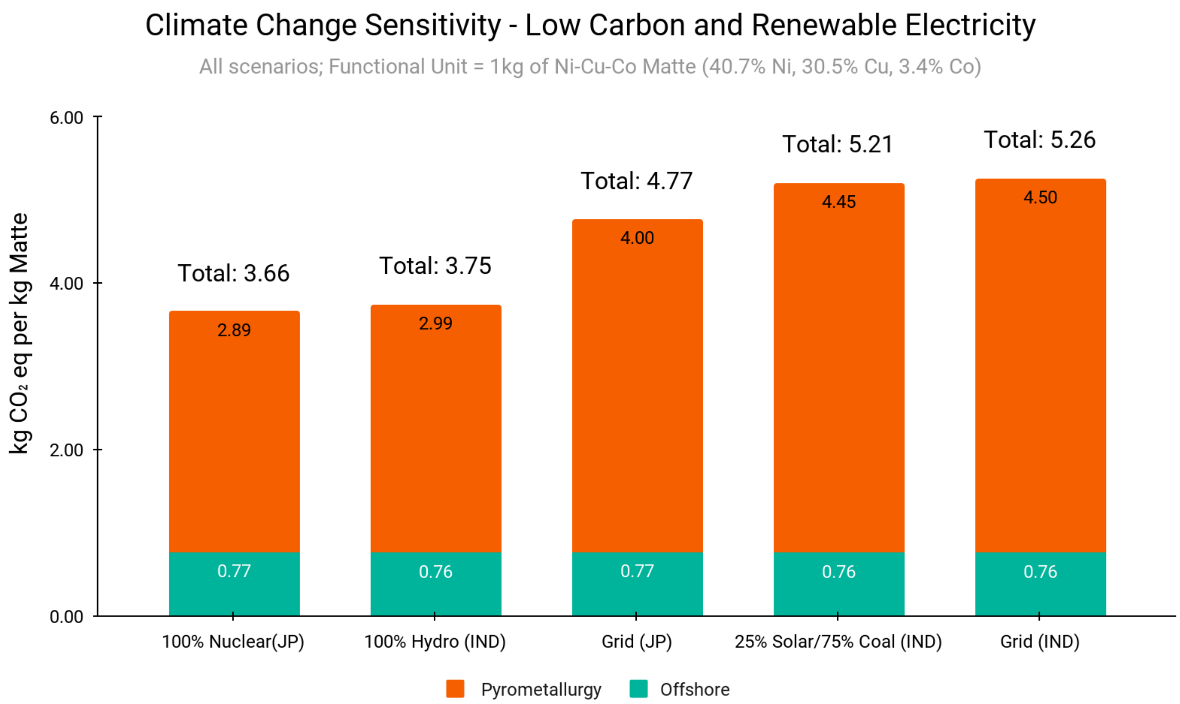

Figure 6: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for production of Ni-Cu-Co matte with the Application of Various Low Carbon and Renewable Electricity Mixes.

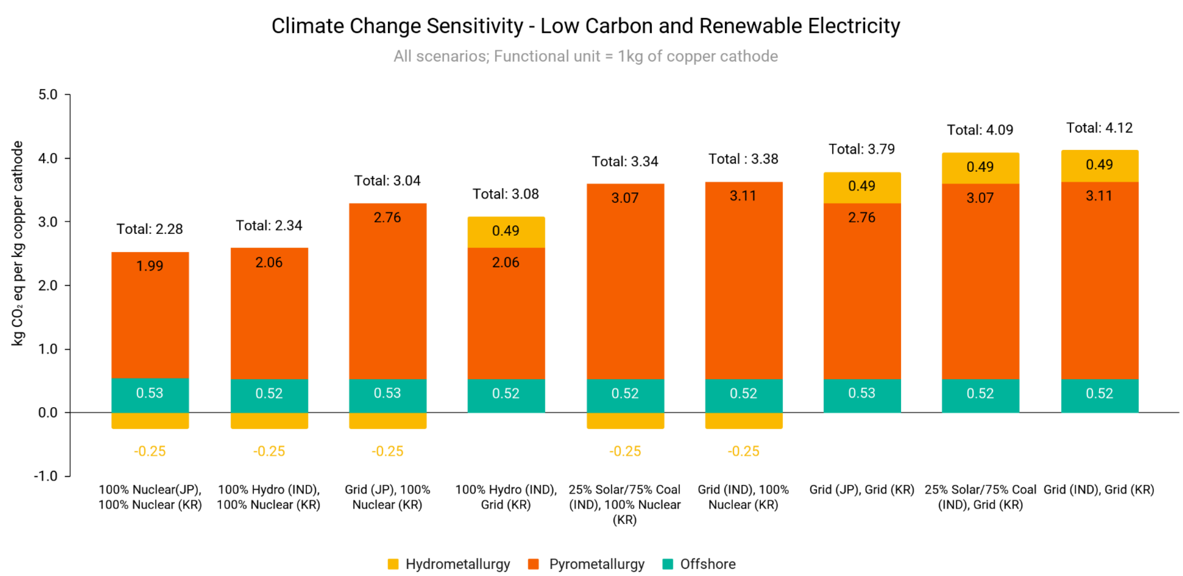

Figure 7: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for the production of copper cathode with the Application of Various Low Carbon and Renewable Electricity Mixes.

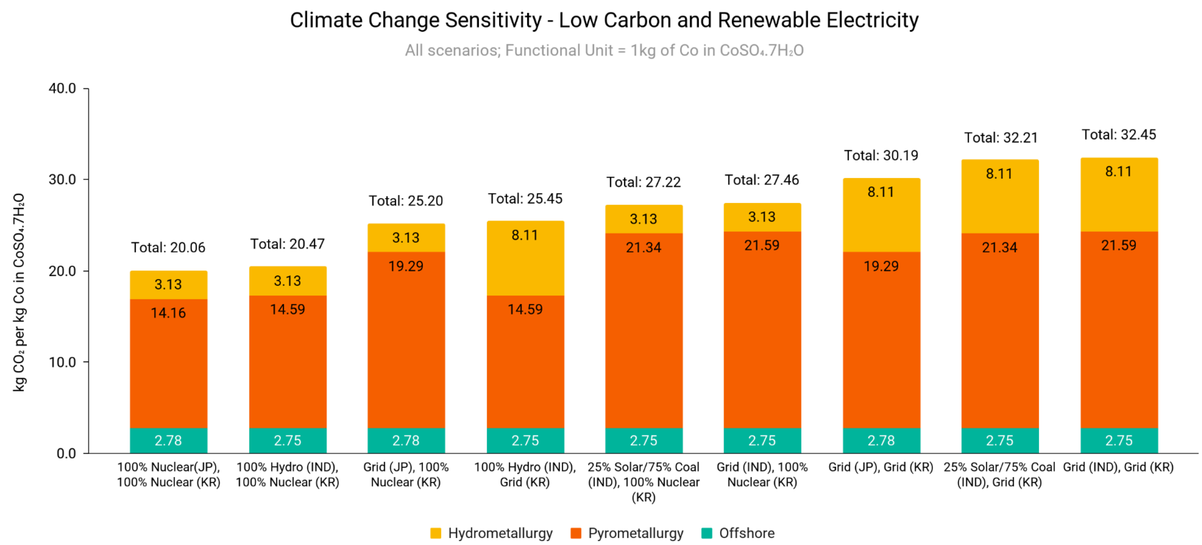

Figure 8: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for the production of $CoSO_4.7H_2O$ with the Application of Various Low Carbon and Renewable Electricity Mixes.

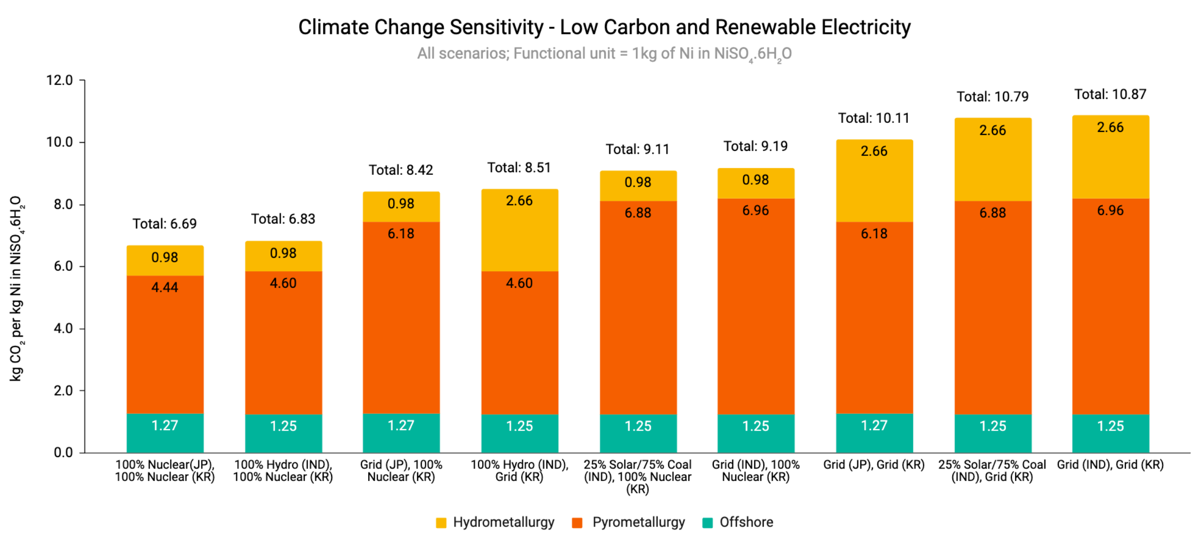

Figure 9: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for the production of $NiSO_4.6H_2O$with the Application of Various Low Carbon and Renewable Electricity Mixes.

1. Contents

List of Tables

List of Figures

12	*Climate Change Contribution Analysis for the Processing of 1kg of Dry Nodules (with Pyrometallurgy in Indonesia).*
13	*Climate Change Contribution Analysis for the Processing of 1kg of Dry Nodules (with Pyrometallurgy in Japan).*
14	*Climate Change Contribution Analysis for the Production of 1kg of Ni-Cu-Co matte (with Pyrometallurgy in Indonesia).*
15	*Climate Change Contribution Analysis for the production of 1kg of Ni-Cu-Co matte (with Pyrometallurgy in Japan).*
16	*Climate Change Contribution Analysis for $MnSiO_3$ Production (with Pyrometallurgy in Indonesia)*
17	*Climate Change Contribution Analysis for $MnSiO_3$ Production (with Pyrometallurgy in Japan).*
18	*Climate Change Contribution Analysis for $NiSO_4{\cdot}6H_2O$ Production (with Pyrometallurgy in Indonesia).*
19	*Climate Change Contribution Analysis for $NiSO_4{\cdot}6H_2O$ Production (with Pyrometallurgy in Japan).*
20	*Climate Change Contribution Analysis for $CoSO_4{\cdot}7H_2O$ Production (with Pyrometallurgy in Indonesia).*
21	*Climate Change Contribution Analysis for $CoSO_4{\cdot}7H_2O$ Production (with Pyrometallurgy in Japan).*
22	*Climate Change Contribution Analysis for Copper Cathode Production (with Pyrometallurgy in Indonesia).*
23	*Climate Change Contribution Analysis for Copper Cathode Production (with Pyrometallurgy in Japan).*
24	*Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the collection and processing of 1kg of dry nodules, when Pyrometallurgy is performed in Indonesia or Japan.*
25	*Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of$MnSiO_3$, When Pyrometallurgy is performed in Indonesia or Japan.*
26	*Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of Ni-Cu-Co matte, when Pyrometallurgy is performed in Indonesia or Japan.*
27	*Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of Copper Cathode, When Pyrometallurgy is performed in Indonesia or Japan.*
28	*Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of $CoSO_4{\cdot}7H_2O$, When Pyrometallurgy is performed in Indonesia or Japan*
29	*Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of $NiSO_4{\cdot}6H_2O$, When Pyrometallurgy is performed in Indonesia or Japan.*
30	*Sensitivity Analysis on the Variation in Global Warming Potential Impacts of processing the dry polymetallic nodules with the Application of Various Low Carbon and Renewable Electricity Mixes.*
31	*Sensitivity Analysis on the Variation in Global Warming Potential Impacts for the production of MnSiO3 with the Application of Various Low Carbon and Renewable Electricity Mixes.*
32	*Sensitivity Analysis on the Variation in Global Warming Potential Impacts for production of Ni-Cu-Co matte with the Application of Various Low Carbon and Renewable Electricity Mixes.*
33	*Sensitivity Analysis of the Variation in Global Warming Potential Impacts of Copper Cathode Production with the Application of Various Low Carbon and Renewable Electricity Mixes.*
34	*Sensitivity Analysis of the Variation in Global Warming Potential Impacts of $CoSO_4{\cdot}7H_2O$ Production with the Application of Various Low Carbon and Renewable Electricity Mixes.*
35	*Sensitivity Analysis of the Variation in Global Warming Potential Impacts of $NiSO_4{\cdot}6H_2O$ Production with the Application of Various Low Carbon and Renewable Electricity Mixes.*
36	*Sensitivity Analysis of the Variation in Global Warming Potential Impacts for the production of 1kg of copper cathode, 1 kg of Ni in NiSO4·6H2O, and 1kg of Co in CoSO4·7H2O when natural gas replaces coal for heating in pyrometallurgy.*
37	*Sensitivity Analysis of Global Warming Potential for TMC's Cu, Ni, and Co Products.*
B1	*Cause-and-effect chain from acidifying emission to change in soil composition (midpoint indicator) and damage to the environment (endpoint indicator)*
B2	*Cause-and-effect chain for nitrogen and phosphorus emissions in aquatic environments, as an example.*
B3	*Impact pathway stages for ionising radiation up to Midpoint by Paulilo et al.*
B4	*Cause-and-effect chain for photochemical oxidant formation and the damage to human health and ecosystems.*
B5	*Cause-and-effect chain human toxicity from emission of chemical substances and damage to human health.*

B6	*The cause-and-effect chain for emissions of ozone-depleting substances (ODS) results in a potential ozone depletion layer (at midpoint level) and damage to human health (at endpoint level).*
B7	*The cause-and-effect chain for resource depletion - metals and minerals.*
C1	*Relative Contribution of all impact categories evaluated in this study per kg of dry nodules collected and processed; Indonesia.*
C2	*Relative Contribution of all impact categories evaluated in this study per kg of dry nodules collected and processed; Japan.*
C3	*Relative Contribution of all impact categories evaluated in this study per kg of Mn in $MnSiO_3$; Indonesia*
C4	*Relative Contribution of all impact categories evaluated in this study per kg of Mn in $MnSiO_3$; Japan*
C5	*Relative Contribution of all impact categories evaluated in this study per kg of Ni-Cu-Co ; Indonesia.*
C6	*Relative Contribution of all impact categories evaluated in this study per kg of Ni-Cu-Co ; Japan.*
C7	*Relative Contribution of all impact categories evaluated in this study per kg of copper cathode ; Indonesia-South Korea.*
C8	*Relative Contribution of all impact categories evaluated in this study per kg of copper cathode; Japan - South Korea*
C9	*Relative Contribution of all impact categories evaluated in this study per kg of Co in $CoSO_4{\cdot}7H_2O$; Indonesia - South Korea*
C10	*Relative Contribution of all impact categories evaluated in this study per kg of Co in $CoSO_4{\cdot}7H_2O$; Japan- South Korea*
C11	*Relative Contribution of all impact categories evaluated in this study per kg of Ni in $NiSO_4{\cdot}6H_2O$; Indonesia-South Korea.*
C12	*Relative Contribution of all impact categories evaluated in this study per kg of Ni in $NiSO_4{\cdot}6H_2O$; Indonesia-South Korea.*

List of Acronyms

Acronym	Meaning
CO_2	Carbon dioxide
DQR	Data quality rating
eq.	Equivalent
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
L	Litres
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
m^2	Metres squared
m^3	Metres cubed
MJ	Megajoules
mol H^+	Moles of protons equivalent (units of acidification potential)
PEF	Product Environmental Footprint
t	Metric tonne(s)
tpa	Tonnes per annum
DE	Direct Emission
IE	Indirect Emissions

Glossary [1,2]

Term	Definition
Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.
Aquatic freshwater eutrophication	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilisers, combustion, sewage systems. Units are in fraction of nutrients reaching the freshwater end compartment (kg P eq).
Aquatic marine eutrophication	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilisers, combustion, sewage systems. Units are in fraction of nutrients reaching marine end compartment (kg N eq).
Background system	Processes over which the LCA-commissioner has little to no direct influence.
Climate change	Increase in the average global temperature resulting from greenhouse gas emissions (GHG). Units are in total radiative forcing as global warming potential – GWP100 (kg CO_2 eq).
Cradle to gate	A partial product supply chain, from the extraction of raw materials (cradle) up to the manufacturer's "gate". The distribution, storage, use stage and end of life stages of the supply chain are omitted.
Cradle to grave	A product's life cycle that includes raw material extraction, processing, distribution, storage, use, and disposal or recycling stages. All relevant inputs and outputs are considered for all of the stages of the life cycle.
Foreground system	Processes which are under the control of the LCA commissioner.
Freshwater and terrestrial acidification	Acidification from air, water, and soil emissions (primarily sulphur compounds) mainly due to combustion processes in electricity generation, heating, and transport. Units are in accumulated exceedance – AE (mol H+ eq).
Freshwater ecotoxicity	Impact of toxic substances on freshwater ecosystems. Units are in the Comparative Toxic Unit for ecosystems (CTUe).
Functional unit	Quantified performance of a product system for use as a reference unit.
Gate-to-gate	A system boundary orientation that allows for the focussed assessment of a particular stage or series of stages within the product supply chain, starting anywhere from the receipt of raw materials, and often ending with the final product produced (ready at the manufacturers 'gate').
Goal	States the intended application, the reasons for carrying out the study, the intended audience, and whether the results are to be used in comparative assertions intended to be disclosed to the public.
Human toxicity, cancer effects - carcinogenic	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured. Units are in the Comparative Toxic Unit for humans (CTUh).
Human toxicity,	Impact on human health caused by absorbing substances through the air, water, and

non-cancer effects - non-carcinogenic	soil. Direct effects of products on humans are not measured. Units are in Comparative Toxic Unit for humans (CTUh).
Ionising radiation, human health	Impact of exposure to ionising radiations on human health. Units are in Human exposure efficiency relative to U-235 (kBq U-235 eq).
Land use (embodied)	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability. Units are based on soil quality index, representing the aggregated impact of land use on: biotic production; erosion resistance; mechanical filtration; groundwater replenishment (dimensionless – pt).
Life cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.
Life Cycle Impact Assessment (LCIA)	Phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
Life cycle Interpretation	Phase in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.
Life Cycle Inventory (LCI)	Phase involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.
Ozone depletion	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation. Units are in Ozone Depletion Potential – ODP (kg CFC-11 eq).
Particulate matter	Impact on human health caused by particulate matter emissions and its precursors (e. g. sulphur and nitrogen oxides). Units are in Impact on human health (disease incidence).
Photochemical ozone formation	Potential of harmful tropospheric ozone formation (“summer smog”) from air emissions. Units are in tropospheric ozone concentration increase (kg NMVOC eq).
Reference flow	Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.
Resource use, fossil fuel depletion	Depletion of non-renewable resources and deprivation for future generations. Units are in abiotic resource depletion, fossil fuels – ADP-fossil (MJ).
Resource use, minerals and metals depletion	Depletion of non-renewable resources and deprivation for future generations. Units are in abiotic resource depletion – ADP ultimate reserves (kg Sb eq).
Scope	Defines the breadth, depth, and the detail of the study which are compatible and sufficient to address the stated goal.
Stripping ratio	A number or ratio that expresses how much waste is mined per unit of ore.
System boundary	Set of criteria specifying which unit processes are part of a product system.

Terrestrial eutrophication	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilisers, combustion, sewage systems. Units are in Accumulated Exceedance – AE (mol N eq).
Water use scarcity footprint	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity. Units are in weighted user deprivation potential (m^3 world eq).

2. Description of ISO-Compliant LCA Methodology

Life Cycle Assessment (LCA) is a method to assess the environmental impacts associated with all stages of a product, process, or activity.[3] Importantly, LCA enables the assessment of direct and indirect impacts that occur throughout the lifecycle of a product or process system, offering insights that may otherwise be overlooked. The holistic approach generates results on how decisions made at one stage of the life cycle might have consequences elsewhere, ensuring that a balance of potential trade-offs can be made, and the shifting of the environmental burdens can be avoided.[4,5] It should be noted that LCA is a suitable method for determining impacts on a global scale and is a complementary approach to local impact assessments such as environmental impact assessments (EIAs) and risk assessments.

This LCA study was conducted according to the requirements of the ISO-14040:2006[1] and ISO-14044:2006[2] standards. In accordance with these standards, LCA has four fundamental steps: (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation (Figure 10).

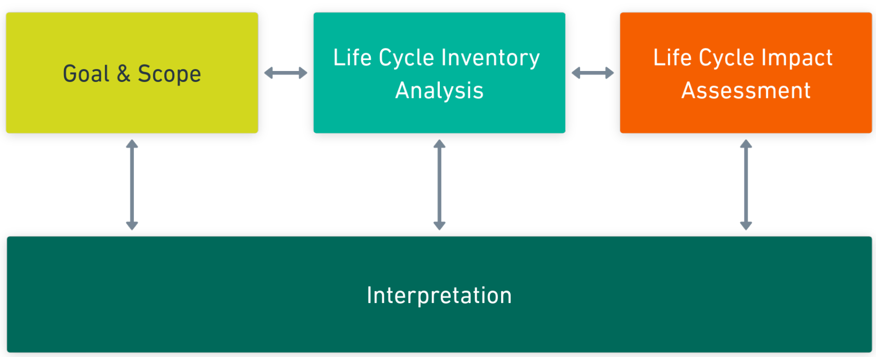

Figure 10: General Phases of a Life Cycle Assessment as Described by ISO 14040:2006.[1]

The goal and scope were defined to be consistent with the study's intended application, the reason for conducting the LCA, and the data available. No bias has been given toward the intended audience.

3. Goal of the Study

The Metals Company ("TMC") commissioned LCA practitioner Minviro Ltd ("Minviro") in August 2023 for the completion of a study which aims to quantify the environmental impacts associated with the production of $MnSiO_3$, Ni-Cu-Co matte, copper cathode, nickel sulphate hexahydrate ($NiSO_4{\cdot}6H_2O$), and cobalt sulfate heptahydrate ($CoSO_4{\cdot}7H_2O$) from polymetallic nodules collected in the NORI-D project.

The goals of this study are as follows:

- Quantify the environmental impacts associated with the production of $MnSiO_3$, Ni-Cu-Co matte, $NiSO_4{\cdot}6H_2O$, $CoSO_4{\cdot}7H_2O$ and copper cathode in relation to the full spectrum of impact categories available with Environmental Footprint (EF) methodology.
- Quantify the environmental impacts associated with a specified quantity of polymetallic nodules processed.
- Identify environmental hotspots within the product system.
- Perform sensitivity analysis assessing the systems response to variations in electricity mix (renewable energy instead of grid mix), fuel type (natural gas instead of coal) and allocation methodology.

It is important to note that this study does not measure environmental impacts on the seafloor, as the LCA methodology currently lacks a framework for adequately quantifying these impacts. This is a limitation of the study. A similar limitation is found when assessing terrestrial mining impacts on forests and other ecosystems as the LCA methodology does not cover these aspects.

The intended application of the LCA study is to provide TMC with environmental insights which will act as a guide to emissions reduction strategies, thereby optimising the environmental impact profile of the overall metal production process. The target audience are investors, customers, and other stakeholders generally interested in the concept of deep-sea minerals.

The LCA conducted is an attributional LCA. This takes an environmental accounting approach that assigns environmental burdens to products based on existing systems upon the physical flows to and from the life cycle of the product and its subsystems – but does not consider marginal and indirect market effects such as changes in supply and demand. This is based upon the physical flows to and from the life cycle of the product and its subsystems.[4] This document has been prepared in accordance with the ISO-14040:2006[1] and ISO-14044:2006[2] standards.

This report has been critically reviewed and the results are intended to be communicated to the public. It is recognised that the data provided by this LCA study may be used by others for comparative assertions in separate future studies. These comparisons should be made on a product system basis only and carried out in accordance with the ISO-14040:2006[1] and ISO-14044:2006[2] standards.

4. Scope of Assessment

The following chapter describes the scope of the LCA study according to goals stated above. This includes, but is not limited to, a project description, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

4.1. Project Description

A significant resource of polymetallic nodules, rich in nickel, manganese, cobalt, and copper, is located on the seafloor in the Clarion-Clipperton Zone (CCZ) of the northeast Pacific Ocean. TMC has identified an opportunity to recover metals from its NORI-D Project area to meet the rising demand for infrastructure development (such as SiMn for the steel industry) and energy transition technologies (Ni, Cu, and Co). Unlike terrestrial mining, which produces large volumes of overburden, the nodules lie unattached on the seafloor, eliminating the need for removing overburden or waste rock. Leveraging this characteristic and the composition of the nodules, TMC aims to minimise waste by creating co-products instead of generating a substantial waste stream, avoiding the need for large-scale waste or tailings facilities.

This report presents the study evaluating the environmental performance associated with the production of various materials of interest to TMC. The distinguishing details of the study presented in this report are summarised in **Table 7**.

Table 7: Key Characteristics and Specifications of the Product System Evaluated in this LCA Study.

Parameter	Details
Quantity of polymetallic nodules processed annually	12 megatonnes (wet) / yr
Core unit processes and base-case location assumptions*	1. Offshore collection of polymetallic nodules in NORI-D Area, CCZ 2. Pyrometallurgy (production of $MnSiO_3$ and Ni-Cu-Co matte) in Indonesia or Japan 3. Hydrometallurgy in South Korea
Co-products	$MnSiO_3$, Ni-Cu-Co matte, $CoSO_4{\cdot}7H_2O$, $NiSO_4{\cdot}6H_2O$ and copper cathode
Other products (by-products)	Ammonium sulfate (assumed to be a substitute for globally produced ammonium sulfate used in the Chemicals and Agriculture Industry) and converter slag (assumed to be used as an aggregate material in road construction)
Functional units	1kg processed dry nodules 1kg of Ni-Cu-Co matte (40.7% Ni, 30.5% Cu, 3.4% Co) 1kg of Mn in $MnSiO_3$ (with a grade of 40% Mn) 1kg of Ni in $NiSO_4{\cdot}6H_2O$ (with a grade of 22.4% Ni) 1kg of Co in $CoSO_4{\cdot}7H_2O$ (with a grade of 21% Co)

	1kg of copper cathode (at a grade of 99.99% Cu)	
Comparative Scenario(s)	N/A	
Sensitivity Analysis (variables assessed)	Sensitivity analysis was conducted to evaluate the impact of various low-carbon and renewable electricity sources that TMC may utilise in the future. Additionally, the analysis considered the potential shift from coal to natural gas for heating, as well as allocation methodology applied.	
Energy Sources	Pyrometallurgy: Indonesia or Japan - Grid (base case) Hydrometallurgy: South Korea - Grid (base case)	
Energy Sources Breakdown	**Indonesian grid mix (2023)** - 65% lignite, 22% nat. gas, 7% hydro, 6% other. **Japanese grid mix (2023) -** 33.4% coal, 45% natural gas, 8% hydro, 4.6% nuclear, 2% petroleum, 2% woodchips, 5.4% other. **South Korean grid mix (2023) -** 33.4% coal, 29.1% nat. gas, 27.6% nuclear, 4.5% solar, 1.1% hydro, 1.0% oil, 3.3% other.	
Energy Source Breakdown (Scenario Analysis)		**Indonesia 25% solar, 75% coal** **Indonesia 100% hydro** **Japan 100% Nuclear** **South Korea 100% Nuclear**
*** When the functional unit of 1kg Ni-Cu-Co matte is used, note that the environmental impacts associated with downstream processes are excluded - namely the transport and hydrometallurgical processing of the Ni-Cu-Co matte***. **** TMC's internal NORI-D Project PFS is not publicly available at the time of release of this study.		

In this project, the polymetallic nodules undergo pyrometallurgy in 2 different locations. The polymetallic nodules collected offshore are shipped to Indonesia where 89% of them undergo pyrometallurgy, the remaining 11% are shipped from Indonesia to Japan for pyrometallurgy. The resulting Ni-Cu-Co matte is then shipped to South Korea where it undergoes hydrometallurgical refining. However, it is important to note that in this LCA study, the total environmental impacts are considered separately for each location where pyrometallurgy occurs. Specifically, the study presents results for the environmental impacts per functional unit when pyrometallurgy is conducted *either* in Indonesia *or* Japan. At this stage, it should also be noted that all ground vehicles used for operational related activities (forklifts, passenger vehicles, etc.) on the metallurgical sites in Indonesia, Japan and South Korea are assumed to be electrical vehicles.

4.2. Product Function

The products evaluated are, $MnSiO_3$, Ni-Cu-Co matte, copper cathode, $NiSO_4{\cdot}6H_2O$ and $CoSO_4{\cdot}7H_2O$. $MnSiO_3$ and Ni-Cu-Co matte are outputs of the pyrometallurgy process. The $MnSiO_3$ serves as a source of manganese and silicate and can be used in the steelmaking industry as alloying agents to produce various grades of steel with unique properties. The matte proceeds to hydrometallurgy where it is further processed to produce copper cathode, $NiSO_4{\cdot}6H_2O$, and $CoSO_4{\cdot}7H_2O$ which all can be used in energy transition technologies.

4.2.1. Functional Units and Reference Flows

LCA uses a **functional unit** as a reference to evaluate the components within a single system or among multiple systems on a common basis. The functional unit is the quantitative reference used for all inventory calculations and impact assessments. The **reference flow** is specific to each product system and represents the amount of product needed to fulfil the function defined by the functional unit.

The functional units and reference units adopted in this study are summarised in **Table 8**.

Table 8: Summary of the Functional Units and Reference Flows Used in this LCA Study.

Parameter	Details
Functional Units	- 1kg processed dry nodules - 1kg of Ni-Cu-Co matte (40.7% Ni, 30.5% Cu, 3.4% Co) - 1kg of Mn in $MnSiO_3$ (with a grade of 40% Mn) - 1kg of Ni in $NiSO_4{\cdot}6H_2O$ (with a grade of 22.4% Ni) - 1kg of Co in $CoSO_4{\cdot}7H_2O$ (with a grade of 21% Co) - 1kg of copper cathode (at a grade of 99.99% Cu)
Reference Flows	- *Similar to the functional units*

The reference flows are the same as the functional units and are defined accordingly. The functional units (and their corresponding reference flows) are aligned with the study's objectives of quantifying the environmental impacts associated with the production of manganese (40%) in $MnSiO_3$, Ni-Cu-Co matte, nickel (22.4%) in $NiSO_4{\cdot}6H_2O$, cobalt (21.0%) in $CoSO_4{\cdot}7H_2O$, and copper cathode (99.99%). This includes evaluating the full spectrum of impact categories available within the EF methodology, as well as assessing the impacts associated with processing a specific quantity of dry polymetallic nodules.

4.3. System Boundary

This LCA is a cradle-to-gate study, meaning the life cycle impact of the product has been assessed from the point of resource extraction/collection (cradle; including pre-extractional removal) to an end-gate. An overview of the system boundaries adopted in this study is presented in this LCA report is presented in **Figure 11**. To understand the full life cycle impact of the products from cradle-to-grave or cradle-to-cradle requires the extension of the system boundary into the use and end of life stages.

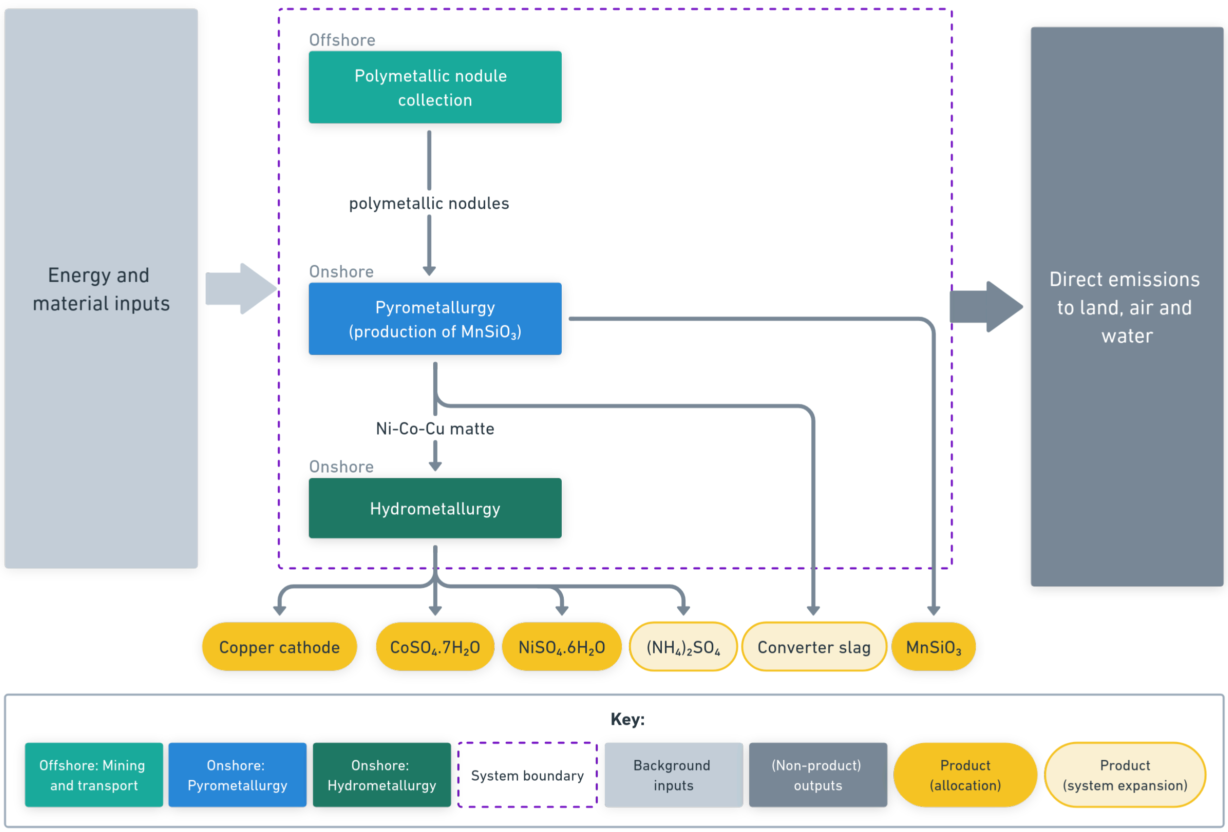

Figure 11: System Boundary Applied to the Life Cycle Assessment Study.

As presented in **Figure 11**, the 'cradle' is the collection of the polymetallic nodules offshore, and the 'gate' has been set to the production of $MnSiO_3$, copper cathode, Ni-Cu-Co matte, $NiSO_4{\cdot}6H_2O$ and $CoSO_4{\cdot}7H_2O$ (unpackaged) ready for shipment. The transport of these products to their end-users, as well as any further downstream uses of the products and their end-of-life processing have been omitted from the system boundary of this LCA. This system boundary was chosen as it aligns with the goal of the study to quantify the environmental impacts associated with the production of $MnSiO_3$, Ni-Cu-Co matte, $NiSO_4·6H_2O$, $CoSO_4·7H_2O$ and copper cathode, and the processing of a specified quantity of dry nodules.

At this stage of project development, some areas have been excluded from the foreground system inventory such as, the impact of capital goods, and packaging materials – see **Table 9** for the approach taken.

Table 9: Inclusions and Omissions From the System Boundary Employed.

Included in System Boundary	Omitted from System Boundary
• Background production of all major raw materials and energy inputs required to produce $MnSiO_3$, copper cathode, Ni-Cu-Co matte, $NiSO_4·6H_2O$ and $CoSO_4·7H_2O$, including all upstream chains. • Transport of polymetallic nodules from offshore operations to TMC's onshore pyrometallurgical operations. • Emission of major wastes to air, water and land including exhaust gases.	• Capital goods and infrastructure such as production of offshore vessels, machinery and construction of buildings. • Treatment of residues formed in the hydrometallurgical step in South Korea. • Employee transport and accommodation. • Production and use of emergency materials and energy such as fire water and emergency generator power. • Reagent and product packaging materials. • Transport of reagents to site. • Sediment and other impacts from dislodging of nodules on the seafloor. Emissions to water (and land/seafloor) from discharging sediments. • Use- and end-of-life phases including transport of the final product to consumers.

The contribution of the omitted flows to the chosen impact categories is assumed to be insignificant or irrelevant to the goal of the study, however it should be noted that for products with a low life cycle impact from production, the relative contribution of the construction consumables could be higher than expected. Whilst these flows have been omitted from the foreground inventory, it is important to note such exclusions do not necessarily apply to the datasets sourced from the ecoinvent database, used to model the background system.

4.4. Product System Boundary Description

NORI-D Project polymetallic nodules sit on the seafloor unattached at depths of around 4500 metres in the abyssal plains. They are composed of nuclei and concentric layers of manganese and iron hydroxides, and are formed by precipitation of metals from the surrounding seawater and sediment pore waters. Nickel, cobalt and copper are also precipitated and occur within the structure of the manganese and iron minerals.

4.4.1. Offshore operations

The main items of off-shore infrastructure are the nodule collector vehicles, the riser, and production, support, and transfer vessels.

The nodules will be collected from the seafloor by self-propelled, tracked, collector vehicles. The collectors will be remotely controlled and supplied with electric power via umbilical cables from the production vessels. The nodules are dislodged from the seafloor using water jets. Collector vehicles then recover a dilute slurry of nodules, sediment, and water from the seafloor. Over 90% of sediment is separated from nodules within the collector and discharged back to the seafloor. A dilute slurry containing the remaining sediment, nodules, and water is then pumped into a steel riser pipe, which transfers the nodules to the surface using an airlift system. Once at the surface, the nodules are transferred to a transfer vessel and onwards to bulk carriers that transfer nodules to select locations for pyrometallurgical and hydrometallurgical processing and refining.

4.4.2. Onshore Operation – Pyrometallurgy

The pyrometallurgical process first starts with a Rotary Kiln Electric Furnace (RKEF) process, followed by sulphidisation and conversion to a sulphidized matte. Outputs from TMC's pyrometallurgy process includes a silicate rich in manganese ($MnSiO_3$) from the RKEF lines which can be sold to the SiMn alloy industry, a converter slag from the sulphidisation and conversion stage which can be used for aggregate in road construction, and a Ni-Cu-Co matte which proceeds to hydrometallurgical refining to recover nickel, copper, and cobalt as refined purified products.

4.4.2.1. RKEF Lines

After the nodules arrive at the pyrometallurgy plant, they are conveyed to the kiln feed bins. The nodules are then fed to the coal fired rotary kilns together with reductant coal and silica flux. The silica flux aids in the formation of the slag phase and is added in amounts to achieve target slag properties. The nodules are roasted and partially reduced from the coal in the kilns. The offgas from the kilns is taken from the feed end of the kiln and sent to particulate cleaning with electrostatic precipitators. The hot calcined nodules from the kilns proceed to electric arc furnaces where they are smelted to produce a molten metal alloy and a large volume of a $MnSiO_3$. The molten alloy proceeds to sulfidation and conversion where it is converted to a matte rich in nickel, copper, and cobalt. The $MnSiO_3$ is cast, crushed, and trucked to port for export to the customers in the SiMn industry. It should be noted that TMC's $MnSiO_3$ product has specifications that differ from standard manganese silicates as TMC's product is pre-reduced and contains higher grades of Mn.

4.4.3. Onshore Operation – Hydrometallurgy

The hydrometallurgical circuit is fed with the Ni-Cu-Co matte from the pyrometallurgical circuit to produce copper cathode, nickel sulfate hexahydrate (NiSO4·6H2O) and cobalt sulfate heptahydrate (CoSO4·7H2O) as well as ammonium sulphate as a co-product. The flowsheet starts with a two-stage leaching circuit starting with atmospheric leaching (AL) to put nickel and cobalt in solution while the remaining Cu-rich matte is treated by pressure oxidative leaching (POX) to produce copper electrolyte which is electrowon to produce copper cathode. The pregnant leach solution from atmospheric leaching is sent to successive impurity removal, solvent extraction stages followed by separate Ni and Co purification-crystallisation circuits to produce battery-grade nickel and cobalt sulphates. An ammonium sulphate product is also formed using a separate crystallisation circuit.

4.4.3.1. Leaching and Copper Electrowinning

The Ni-Cu-Co matte from the pyrometallurgy circuit is ground in a mill to reduce particle size and pulped before leaching. The pulped matte is then pumped to the first stages of atmospheric leaching where sulphuric acid, oxygen, and spent electrolyte from electrowinning leach Ni and Co into solution. In the final stages of atmospheric leaching, no oxygen is added, promoting metathesis reactions whereby Cu from the solution substitutes the remaining Ni in sulfide phases from the matte. This leads to a PLS enriched in Ni and Co, and a residual matte depleted in Ni/Co but upgraded in Cu. The upgraded matte then proceeds to pressure oxidative leaching at 220 degrees Celsius using spent electrolyte, make-up acid, and oxygen in an autoclave. The copper rich solution from the autoclave is purified with potassium metabisulfite (KMBS) to remove impurities, cooled, and sent to copper electrowinning where copper cathodes are produced.

4.4.3.2. Cobalt Solvent Extraction

The nickel-cobalt-rich pregnant leach solution from atmospheric leaching proceeds to an iron removal stage where ammonia is added to raise the pH and precipitate iron. The Iron-free solution then proceeds to cobalt SX where Co is extracted using an organic solvent (Cyanex 272) and then stripped from the organic solution using diluted acid.

The cobalt strip solution is then purified to remove impurities through successive Cu and Mn Ion Exchange (IX) stages. The purified cobalt solution is then sent to successive evaporation, crystallisation and centrifugation stages before being crystallised to produce battery-grade $CoSO_4 \cdot 7H_2O$ crystals.

*Note: The iron-rich residue is assumed to be landfilled, however it was excluded from this study as no data was available. It should also be noted that when considering the product system the impacts from treatment of the residue will likely be negligible.

4.4.3.3. Nickel Solvent extraction

The cobalt-free raffinate from Co SX then proceeds to Ni SX where Ni is extracted using neodecanoic acid. The loaded organic solution is then scrubbed of impurities, and stripped with sulfuric acid. The stripped solution then proceeds to successive evaporation, crystallisation and centrifugation stages before being crystallised to produce battery-grade $NiSO_4 \cdot 6H_2O$ crystals.

The remaining nickel raffinate has a high ammonia content. Similarly, this raffinate is sent to successive evaporation, crystallisation and centrifugation stages before being dried to produce ammonium sulphate.

4.5. Allocation

In LCA, it is critical to ensure that environmental impacts are divided among the different products of a process operation in a way that is scientifically valid and best practice. Following the guidance provided in ISO-14044:2006 standard, it is recommended to avoid allocation as much as possible.[2] Allocation refers to the process of making decisions on how to distribute environmental impacts among different products. However, this approach can introduce uncertainty into the LCA results, as different allocation methods can yield varying outcomes. Moreover, individual allocations methods can be controversial because they may assign a disproportionate share of environmental impacts to a specific product or process.

System expansion is recommended over allocation as it eliminates the co-products from the product system by subtracting the inventory flows associated with a 'conventionally' produced product (equivalent to the co-product in question) from the life cycle inventory.[4] This is done by selecting a functionally equivalent produced by an alternative process. If this is not possible, allocation methods must be used. Since alternative production routes are often available for non-metals, this is the preferred approach for dealing with co-products such as slags, process gases and other non-metal co-products.[5]

Subdivision is also recommended over allocation. When possible, the product system should be subdivided into the sub-processes that are specific to each co-product. This approach avoids allocation because the inputs and outputs are directly related to the manufacturing of the co-product and not shared with any other co-products. Subdivision may not be feasible for complex, multi-output processes, such as those found in many metal processing operations. In these circumstances, system expansion or co-product allocation should be considered.[5]

Co-product allocation distributes the impacts of the multi-output process to the various outputs using a relationship between those products. For metals, mass and economic (or market value) are the most common methods of allocation, however other forms of allocation may also be used such as energy or molar based allocation.

Allocation based on energy leads the outputs to be partitioned according to the amount of energy that is stored in the co-products (as a result of fuel based inputs).

Allocation by mass is generally preferred when the economic value per unit of output between coproducts is similar. This is due to the fact that mass remains relatively constant over time, while market value is subject to market fluctuations. As guidance, EN 15804 defines “small” as less than a 25% difference in value.[5]

Allocating based on the price of a product is known as economic allocation. Using this approach, total impacts are allocated with respect to the economic value of the individual outputs. The market values of the outputs are averaged over a certain time period; longer periods are recommended in order to reduce the impact of random price spikes and drops.

It is important to note that the version of the ecoinvent database used for modelling the background system adopts the "Allocation, cut-off by classification" system model, which, when the issue of multifunctionality arises, ordinarily defaults to the use of economic allocation (allocation based on product price) and to a minor extent, allocation based on energy.

In this LCA study, environmental impacts in the pyrometallurgical circuits were partitioned between the co-products ($MnSiO_3$ and Ni-Cu-Co matte) based on mass and energy allocation. In the hydrometallurgical circuit, environmental impacts were partitioned between the co-products (Ni, Cu, and Co) on the basis of economic allocation using 10-year average values for the price of copper, nickel and cobalt. System expansion (by substitution) was applied to account for ammonium sulfate and converter slag produced during the sulphidisation and conversion stages. Ammonium sulfate was assumed to substitute globally produced ammonium sulfate for the Chemicals and Agriculture industry, while converter slag was assumed to serve as aggregate in road construction. Where the co-products did not share similar processes, sub-division was carried out. The method of co-product management is summarised in **Table 10**.

Table 10: Methods of Co-product Management Applied in this Study.

Product	Annual production (tonnes/year)	Price (US$/tonne)	Economic allocation factor*	Economic allocation factor (sensitivity analysis)**	Mass allocation factor	Metal Mass allocation factor (sensitivity analysis)**	System expansion
Mn in $MnSiO_3$	2,796,101	-	-	-	90.5%	-	-
Ni-Cu-Co matte	294,576	-	-	-	9.5%	-	-
Copper cathode	89,620	6873	21.0%	29.2%	-	40.8%	-
Co in $CoSO_4 \cdot 7H_2O$	9,856	46069	15.5%	10.7%	-	4.5%	-
Ni in $NiSO_4 \cdot 6H_2O$	119,922	15540	63.5%	60.1%	-	54.7%	-
Ammonium sulfate	358,820	-	-	-	-	-	Substitution of globally produced ammonium sulfate
Converter slag	940,033	-	-	-	-		Substitution of commercially produced crushed gravel

*The 10-year average prices for the metals are for the years 2014-2023. [43.44]
**Economic allocation using a forecasted 10-year average market value, using data sourced from the CRU Group.[45]

4.6. Cut-Off Criteria

Cut-off criteria in LCA determine which inputs are included in the assessment based on their mass, energy, or environmental significance. In this study, all flows provided by TMC for the foreground processes within the system boundary were considered. Cut-off criteria inherent to the project's early stage of development have been applied during TMC's LCI data collection.

Examples of excluded flows include upstream transport of reagents, consumables like pipes, wear plates, gravity separation trays, reagent packaging materials, light vehicle use, ancillary services, and staff transport and accommodation. It is also important to note that, specific inputs to the hydrometallurgical process – such as Copper IX resin, flocculant, coagulant, Di(2-ethylhexyl)phosphoric acid, neodecanoic organic solvent, and activated carbon – have been excluded from the life cycle inventory (LCI). These materials are used in relatively small quantities, and due to a lack of reliable and representative data related to their production, their contribution to the overall environmental impact is considered negligible. In some cases, cut-off effects may also arise due to gaps in the foreground data, either provided by TMC or collected by Minviro. Additionally, missing data in background flows from the ecoinvent database may result in cut-off effects in the background datasets.

4.7. Selection of LCIA Methodology

The impact assessment methodology applied to this LCA is EF.[7] The EF characterisation methodology was originally based on the International Reference Life Cycle Data System (ILCD) recommended methods, but several methods have since been modified and updated by the European Commission as part of the ongoing development of the Product Environmental Footprint (PEF) initiative.[7,8] EF characterisation factors are considered to be the most robust and up-to-date available for the European context, are widely used and respected within the LCA community, and are required for Product Environmental Footprint studies and Environmental Product Declarations under ISO-14025:2006.[9]

4.8. Selection of Impact Categories

The LCIA categories selected for detailed investigation in this study include climate change, as well as all of the other impact categories available through the EF methodology. These are midpoint indicators which focus on single environmental problems. Climate change impact is an essential consideration for TMC's stakeholders, including their customers in the downstream use-phase of the product's life cycle. The evaluation of these impact categories satisfies the goal of the study, and will enable the consideration of environmental burden shifting and circularity benefits with respect to the other EF impact categories.

LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. The ILCD handbook addresses the scientific robustness and certainty of each impact category selected.[8]

Detailed description of the climate change impact category is presented in the next subsection. The descriptions of each of the other EF environmental impact categories evaluated are provided in **Appendix B**.

4.8.1. Climate Change

Baseline model of 100 years based on IPCC 2021.[10]

Climate change can be defined as the change in global temperature caused by the greenhouse effect of “greenhouse gases” released by human activity. There is now scientific consensus that the increase in these emissions is having a noticeable effect on climate. Climate change is one of the major environmental effects of economic activity, and one of the most difficult to control because of its global scale.[11] The environmental characterisation model is based on factors developed by the UN’s Intergovernmental Panel on Climate Change (IPCC). Factors are expressed as Global Warming Potential (GWP) over the time horizon of different years, the most common historically being 100 years, measured in the reference unit, kg CO_2 eq.

The Greenhouse Gas (GHG) Protocol identifies three ‘scopes’ of GHG emissions which have been included in this study, however, it should be noted that scopes of emissions are not a framework inherent to LCA. The GHG Protocol defines the various scopes of emissions as:

- **Scope 1**: Direct GHG emissions (e.g. furnace off-gas, combustion of fuels)
- **Scope 2**: Indirect GHG emissions from consumption of purchased electricity, heat, or steam (e.g. emissions embodied in grid power or embodied in steam at an industrial park)
- **Scope 3**: Other indirect emissions such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g. transmission and distribution losses) not covered in scope 2, outsourced activities, and waste disposal. Scope 3 emissions can be either “upstream” or “downstream”. In a cradle-to-gate LCA, “upstream” scope 3 must be included.

5. Life Cycle Inventory (LCI) Analysis

5.1. Data Collection and Calculation

This study was desk-based, meaning that all data was either provided by TMC, collected from public sources, or assembled from public and private databases.

Foreground data (comprising what is referred to as the 'foreground system') refers to the specific inputs, outputs, and processes directly related to the system under study. Foreground data, relating to offshore operations, pyrometallurgy and hydrometallurgy processes were sourced from TMC's internal NORI-D project Pre-feasibility study (PFS) (November 2024) and from their SK-1300 compliant NORI-D Initial Assessment (March 2021).[47] The LCI flows were grouped into life cycle stages.

Background data (which are used to model the 'background system') refers to the material and energy inputs that are delivered to the foreground system under study. Typically aggregated, represent average values for a given region or industry sector and are sourced from reference databases. In this study, background datasets were the ecoinvent database 3.10. The ecoinvent database comprises datasets that represent individual processes of human activities and their exchanges with the biosphere and technosphere. The consistency and cohesion of these background datasets increases the credibility and acceptance of the LCA models built using them. It must be noted that although the ecoinvent database is extensive, it is critical to understand the uncertainty, technological and geographical relevance of the data points.[6]

Assumptions and limitations for this study are discussed in **Section 6**. An energy, material, and emissions flow summary is included below in **Section 5.2**.

5.2. Life Cycle Inventory Data

In relation to the modelled base-case scenario, **Table 11** details the energy, material and emissions flows, and the background data used in the study for each inventory item.

Table 11: Summary of the LCI (Country codes: RoW = rest of world, GLO = global, US-TRE = texas regional, KR = south korea)

Inventory Item	Exchange type	Quantity	Units	ecoinvent process / additional notes	Country Code
Offshore Mining					
Marine Fuel (IE + DE) - Indonesia	Input	625,225	tonnes / yr	heavy fuel oil, burned in refinery furnace	RoW
Marine Fuel (IE + DE) - Japan	Input	632,375	tonnes / yr	heavy fuel oil, burned in refinery furnace	RoW
Wet nodules collected	Output	12,000,000	tonnes / yr	*Input to the pyrometallurgy (production of $MnSiO_3$ and Ni-Cu-Co matte) stage*	-
Total dry Nodules processed	Output	9,120,000	tonnes / yr	-	-
Pyrometallurgy (Production of $MnSiO_3$ and Ni-Cu-Co Matte)					
Total Dry nodules	Input	9,120,000	tonnes / yr	-	
Processed in Japan	Input	1,000,000	tonnes / yr	-	
Processed in Indonesia	Input	8,120,000	tonnes / yr		
Silica	Input	525,491	tonnes / yr	market for silica sand	GLO
Reductant coal	Input	884056			
Coal (natural gas replacement) (	input	609984	tonnes / yr	market for hard coal	RoW
Natural gas (*sensitivity analysis*)	Input	347587	tonnes / yr	market for natural gas liquids	GLO
Make up water	Input	9,685,171	m3 / yr	market for tap water	RoW
Electrode paste	Input	11,028	tonnes / yr	50% 'graphite production' - RoW 50% 'market for carbon black' - GLO	RoW GLO
$MnSiO_3$	Output	6,990,252	tonnes / yr	-	-
Silica	Input	235,283	tonnes / yr	market for silica sand	GLO
Liquid sulfur	Input	57,972	tonnes / yr	market for sulfur	GLO
Converter slag	Output	940,033	tonnes / yr	market for gravel, crushed	RoW
Ni-Cu-Co matte	Output	294,576	tonnes / yr	-	-
Electricity (operations)	Input	4,167,730	MWh / yr	electricity, high voltage, production mix market for electricity, high voltage	ID JP
Electricity (vehicles)	Input	17,548	MWh / yr	electricity, high voltage, production mix market for electricity, high voltage	ID JP
Hydrometallurgy					
Ni-Cu-Co matte	input	294,576	tonnes / yr	-	-
H_2SO_4 (93%)	input	329,290	tonnes / yr	market for sulfuric acid	RoW
Anhydrous liquid ammonia	input	90,385	tonnes / yr	market for ammonia, anhydrous, liquid	RoW
Cyanex 272	input	110	tonnes / yr	market for organophosphorus-compound, unspecified	GLO

Diluent	input	222	tonnes / yr	market for kerosene	RoW
Potassium Metabisulfite	input	4	tonnes / yr	market for potassium sulfate	RoW
Potassium hydroxide	input	3,011	tonnes / yr	market for potassium hydroxide	GLO
Natural Gas	input	66,506	tonnes / yr	heat production, natural gas, at boiler modulating >100kW	RoW
Electricity (Vehicles)	input	5,972	MWh / yr	electricity, high voltage, production mix	KR
Electricity (Operations)	input	497,489	MWh / yr	electricity, high voltage, production mix	KR
Ni in $NiSO_4.6H_20$	output	119,922,528	kg / yr	-	
Cu cathode	output	89,620,416	kg / yr	-	
Co in $CoSO_4.7H_20$	output	9,856,896	kg / yr	-	
Ammonium sulfate	output	358,819,672	tonnes / yr	market for ammonium sulfate	RoW

Copper IX resin, flocculant and coagulant, Di(2-ethylhexyl)phosphoric acid, neodecanoic organic solvent and activated carbon input to the hydrometallurgy section of the product system have been omitted from the LCI due to only small amounts being used and unrepresentative data on them being present.

5.2.1. Sensitivity Analysis

Sensitivity analysis was conducted assessing how total climate change impacts vary based on alternative low-carbon and renewable electricity sources that TMC may utilise in the future. This was done by switching a number of ecoinvent processes incorporated into the background system of the base-case scenario. A summary of the background data points used in each scenario is highlighted in **Table 12**.

Table 12: Summary of the Life Cycle Inventory used for the Sensitivity Analysis.

Sensitivity scenario	ecoinvent process / additional notes	Country Code
Indonesian pyrometallurgy plant: Electricity mix comprising 25% solar and 75% coal combustion.	25% - electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	ID
	75% - electricity production, lignite	ID
Indonesian pyrometallurgy plant: 100% hydroelectricity.	electricity production, hydro, reservoir, tropical region	ID
Japanese pyrometallurgy plant: 100% nuclear energy for electricity	electricity production, nuclear, pressure water reactor, heavy water moderated	JP
Natural Gas for heating	heat production, natural gas, at boiler modulating >100kW	RoW
South Korean hydrometallurgy plant: 100% nuclear energy.	electricity production, nuclear, pressure water reactor	KR

5.3. Data Quality Assessment

In evaluating the quality of the foreground and background data used in the LCA model, several key criteria were considered:

- Technological, temporal, and geographical representativeness: data is deemed representative when it aligns with the geographical, temporal, and technological aspects outlined in the study's goal and scope. The use of representative data for all modelled processes enhances the overall quality of the study results and conclusions. In cases when primary data is not available, the best-available proxy data, preferably sourced from databases or academic LCA literature, is used.
- Completeness: In the context of LCA, completeness refers to the extent that all of the relevant inputs and outputs associated with a unit process has been accounted for in the dataset.
- Precision: Precision in data used for analysis refers to its consistency, repeatability, and level of detail. Precise data show minimal variability when measured or calculated repeatedly, indicating high reliability. Factors affecting precision include measurement techniques, instrumentation quality, modelling approaches, and data source uncertainty. Measured primary data is the most precise, followed by calculated data, literature data, and estimated data. However, measured data can be precise but inaccurate. Cross-validation enhances accuracy.
- Methodological appropriateness and consistency: Data is considered appropriate and consistent when differences between data reflect genuine disparities between distinct product systems and are not the result of inconsistencies in data collection or modelling.

Table 11 presents the grading system of data quality indicators.[8] An evaluation of the data quality for this LCA can be found below in **Section 5.3.1**.

Table 13: Grading Guidelines for Data Quality Assessment as Environmental Footprint 2.0 Pedigree Matrix[8] *(PEF = Product Environmental Footprint).*

Data Quality Indicator	Very Poor	Poor	Fair	Good	Very Good
Technological Representativeness	Old to dissimilar technology used	Technology dissimilar to what is used	Generic technology average	From technology specific to the application	All technology aspects of data have been modelled
Temporal Representativeness	The time period for which the dataset is valid is more than 8 years old	The time period for which the dataset is valid is less than 8 years old	The time period for which the dataset is valid is less than 6 years old	The time period for which the dataset is valid is less than 4 years old	The time period for which the dataset is valid is less than 2 years old
Geographical Representatives	Data represented is from a distinctly dissimilar region of project location	Similar regions are represented in data	Global average is represented in data	Country of interest is represented in the data	Region of interest is fully represented in data
Completeness	Representativeness unknown or data from a small number of sites and from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations
Precision	Rough estimate with known deficits	Estimates based on calculations not checked by the reviewer	Estimates based on expert judgement	Estimates based on measured and prior values	Measured and verified values with <7% uncertainty
Methodological Appropriateness and Consistency	Attribution process-based approach and following none of the three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Attribution process-based approach and following one out of three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Attribution process based approach and following two out of three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Attribution process based approach and following three method requirements of the PEF guide: dealing with multi functionality, end of life modelling, and system boundary	Full compliance with all requirements of the PEF guide

5.3.1. Data Quality Assessment Results

The quality of the foreground and background data comprising the LCI was evaluated in accordance with the grading system (the pedigree matrix) presented in **Table 13** , assessing criteria such as technological representativeness, temporal representativeness, geographical representativeness, completeness, precision, and consistency.

The results of the data quality assessment are presented below in **Tables 14** and **15**. For details relating to the data collection and calculation procedures, refer to **Section 5.1**.

Table 14: Summary of Data Quality Assessment - Representativeness.

Data Quality Indicator	Foreground Data		Background Data	
	Grading	Reasoning	Grading	Reasoning
Technological Representativeness	Fair	Project scenario based from TMC's internal NORI-D Project PFS (October 2024) and onshore technical data was taken from SK-1300 compliant NORI-D Project Initial Assessment (March 2021).[47] Though a PFS has a higher degree of confidence than than a PEA, it has a lower degree of confidence than an FS, and even lower than operational data. As such, it has been given a rating of fair.	Good	In a small number of instances, wholly representative ecoinvent background datasets were unavailable (as listed in **Section 6**), necessitating the use of proxy background datasets.
Temporal Representativeness	Good	The foreground data was collected over the year of 2021, and then upgraded with the completion of TMC's internal NORI-D Project PFS (November 2024) and so is representative of the assumed reference year of the project.	Very good	The background data points used were sourced from version 3.10 of the ecoinvent database, which at the time each project was conducted was the latest version available.
Geographical Representativeness	Fair	Specific data relating to the transport of nodules have been used – taking into account the actual distance between the offshore mining site and the pyrometallurgy plant (where nodules are processed)	Fair	Electricity mixes representative of the country in which they are applied have been used. For the remaining background data points, only datasets representing rest-of-world (RoW) or global (GLO) averages were available.

Table 15: Summary of Data Quality Assessment - Other Indicators.

Data Quality Indicator	Grading	Reasoning
Completeness	Good	Good foreground data was supplied by TMC. TMC collected the foreground data from operations at one site, and In Minviro's expert opinion, little-to-no difference in the LCI (with the exception of the electricity related inputs) will change with location.
Precision	Good	The majority of foreground data provided by the client have been measured.
Methodology Appropriateness and Consistency	Fair	Attribution process based approach and following two out of three method requirements of the PEF guide. As the use-phase and end of life-phase of the products were not included, the study only covers a part of the product life cycle.

6. Assumptions and Limitations

- It is assumed that 12 megatonnes of wet polymetallic nodules are extracted annually.
- In the base-case scenario, the collected polymetallic nodules are transported to either Japan or Indonesia where they undergo processing (pyrometallurgy). The Ni-Cu-Co matte that is produced is then shipped to South Korea where it undergoes hydrometallurgy. At the South Korean plant, it is assumed that a grid electricity mix is applied.
    - For pyrometallurgy carried out in Japan, the grid electricity mix comprises 33.4% hard coal combustion, 45% natural gas combustion, 8% hydroelectricity (run-of-river), 2.6% nuclear energy (via boiling water reactor), 2% nuclear (via pressure reactor), 2% petroleum, 2% woodchip combustion and 5.4% generated by other means.
    - For pyrometallurgy carried out in Indonesia, the grid electricity mix comprises 65% lignite-generated electricity, 22% natural gas combustion, 7% hydroelectricity (reservoir), and 6% generated by other means.
    - For hydrometallurgy carried out in South Korea, the grid electricity comprises 33.4% coal, 29.1% nat. gas, 27.6% nuclear, 4.5% solar, 1.1% hydro, 1.0% oil, and 3.3% generated by other means.
- The pyrometallurgical process assumes coal is used as the reductant. Due to current infrastructure limitations at the scenario facilities, coal is also assumed to be the primary heat source, as access to natural gas is restricted.
- For instances where wholly representative background data points are not available through the ecoinvent database, data points representing what are deemed to be suitable proxies materials have been used. Examples are the following:
    - Potassium metabisulfite (KMBS) (input to hydrometallurgy process – specifically during Fe removal) – Potassium sulfate used as a proxy.
    - Cyanex-272 (input to input to hydrometallurgy process – specifically during Co solvent extraction) – Organophosphorus-compound used as a proxy.
    - Diluent (input to input to hydrometallurgy process – specifically during cobalt solvent extraction) was assumed to be kerosene.
    -

- The inputs of Copper IX resin, flocculant, coagulant, Di(2-ethylhexyl)phosphoric acid, neodecanoic organic solvent, and activated carbon in the hydrometallurgical process have been excluded from the life cycle inventory (LCI). This is due to the relatively small quantities of these materials used in the system, and the lack of representative data for their inclusion. As a result, their contribution to the overall environmental impact is considered negligible.
- Pyrometallurgy yields three marketable products: $MnSiO_3$, Ni-Cu-Co Matte and converter slag. A mixture of co-product management methods were employed to resolve the issue of multifunctionality. Mass allocation was applied to the $MnSiO_3$ and Ni-Cu-Co matte products where processes were shared. Allocation factors of 90.5% and 9.5% were assigned respectively. Since the $MnSiO_3$ leaves the system before subsequent sulfidation and conversion, these steps were entirely allocated to the matte. System expansion was conducted on the converter slag and the system was credited.
- In relation to the Pyrometallurgy section, energy-based allocation was applied to coal. Specifically:
  - 100% of the bituminous coal was for reduction purposes, however 20% is lost to heat. Therefore 80% of the coal was used as a reductant of which 62% was allocated to TMC’s $MnSiO_3$ and the remainder to the Ni-Cu-Co matte.
  - The 20% of bituminous coal that was lost to heat was used to meet the heat demand of the process. Of this 20%, 92.5% was allocated to TMC's $MnSiO_3$ and the remainder to the Ni-Cu-Co matte.
  - 100% of the replacement coal which substituted natural gas was used for heating purposes. 92.5% of the replacement coal was allocated to TMC’s $MiSiO_3$ and the remainder to the Ni-Cu-Co matte.
- Hydrometallurgy yields four marketable products: $NiSO_4 \cdot 6H_2O$, $CoSO_4 \cdot 7H_2O$, copper cathode and ammonium sulfate. A mixture of co-product management methods were employed to resolve the issue of multifunctionality. Economic allocation was applied to $NiSO_4 \cdot 6H_2O$, $CoSO_4 \cdot 7H_2O$, copper cathode products, with allocation factors of 63.5%, 15.5% and 21.0% assigned. Ammonium sulfate has various applications within the Chemicals and Agriculture Industry. As such, the system expansion was performed on TMC’s ammonium sulfate, assuming that it substitutes globally commercially produced ammonium sulfate.

6.1. Limitations

The primary limitation of this study is the inherent uncertainty of conducting an LCA at the pre-feasibility stage. Since the project is at the pre-feasibility stage, some data and process definitions (such as processing pathways, processing locations, and production plans) may change as it progresses toward full-scale operation. To enhance accuracy, updating the LCA once TMC's facilities are fully operational is recommended, allowing for refined assumptions.

Additionally, this study does not assess the environmental impacts related to polymetallic nodule collection at the seafloor. These impacts lie outside the scope of the current analysis.

7. Results

Results for the selected impact categories are presented below. Groupings into life cycle stages are based on the system boundaries described in **Section 4.3.** Contribution analysis figures aggregate the contributors to each impact category worth less than 1% of the total environmental impact as ‘other’ for aesthetic purposes. Environmental credits that have an absolute impact of less than 1% are also included in the other category. These small contributors are still included in the overall result.

Graphical depictions of LCIA results should not be used for implicit comparisons and conclusions outside of the goal and scope of this study. Furthermore, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Note: *At the request of TMC, the acronyms for Direct Emissions (DE) and Indirect Emissions (IE) have been used throughout this report to align with their internal interpretation and facilitate understanding of the results. IE are the emissions from the production of inputs. DE are the emissions from the direct use of such inputs, e.g. marine gas oil, coal, electricity.*

7.1. Climate Change Impact

A total of six functional units have been employed, allowing for the quantification of environmental impacts associated with the processing of 1kg of dry polymetallic nodules, the production of 1kg of Ni-Cu-Co matte, Mn (contained in $MnSiO_3$), Ni (contained in $NiSO_4 \cdot 6H_2O$), Co (contained in $CoSO_4 \cdot 7H_2O$), and copper cathode.

In this model, we assume that the polymetallic nodules collected offshore are shipped to Indonesia where 89% undergo pyrometallurgy. The remaining 11% are shipped from Indonesia to Japan for pyrometallurgy. The resulting Ni-Cu-Co matte from both locations are then shipped to South Korea for hydrometallurgical refining. However, it is important to note that the total environmental impacts are considered separately for each location where pyrometallurgy occurs. Specifically, the results are presented for the environmental impacts per functional unit when pyrometallurgy is conducted either in Indonesia or Japan.

The following climate change results subsections have been presented per functional unit studied, as well as per location of pyrometallurgy performed.

7.1.1. Functional unit: 1kg dry nodules processed

This section presents the climate change impact associated with the processing of 1kg of dry nodules under two scenarios: one where pyrometallurgical processing takes place in Indonesia and another where it occurs in Japan. The analysis includes emissions from offshore operations, transshipment, and pyrometallurgical activities, with detailed results for both scenarios illustrated in **Figure 12** (Indonesia) and **Figure 13** (Japan).

7.1.1.1 Pyrometallurgy in Indonesia

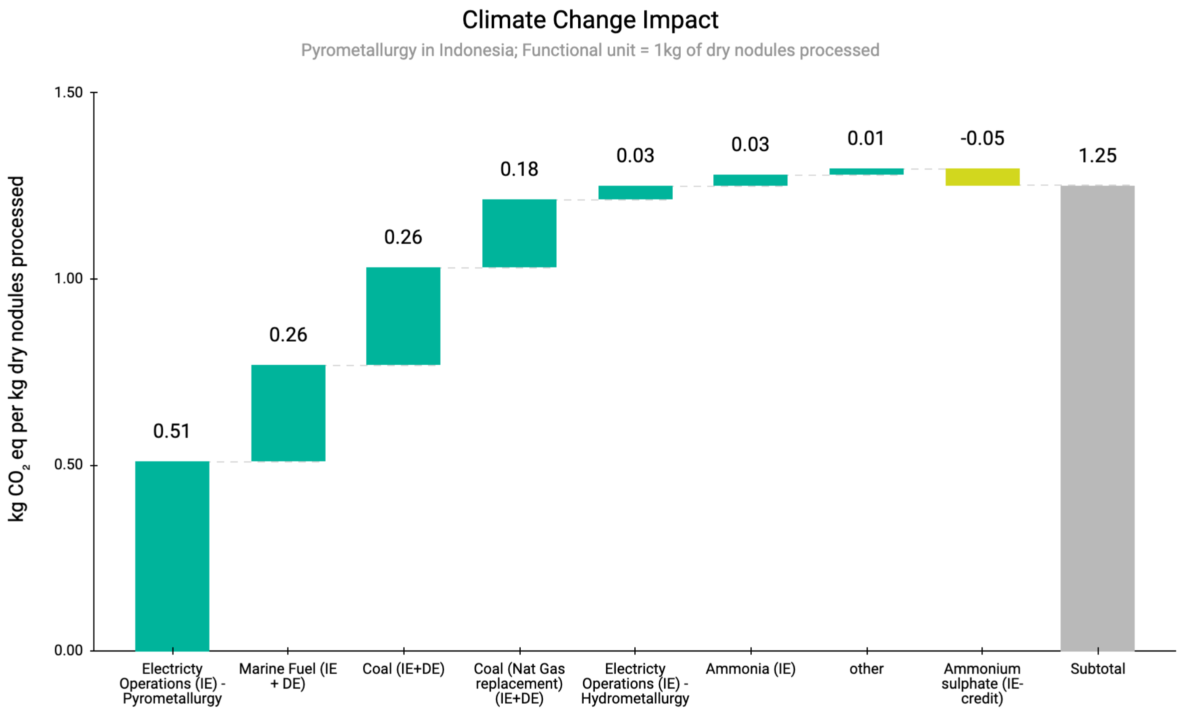

Figure 12: Climate Change Contribution Analysis for the Processing of 1kg of Dry Nodules (with Pyrometallurgy in Indonesia).

When pyrometallurgical processing is conducted in Indonesia, the total climate change impact amounts to 1.25 kg CO_2 eq. per kg dry nodule processed. Main contributors to this impact are:

- **Electricity** usage during TMC's pyrometallurgical operations in Indonesia contributes approximately 0.51 kg CO_2 eq., accounting for 41% of the total climate change impact. This is largely due to Indonesia's fossil fuel-dominated energy grid.
- **Marine fuel** burned by vessels during offshore operations contributes approximately 0.26 kg CO_2 eq., or 21% of the total impact. This is driven by the combustion of marine fuel oil, which has a significant carbon footprint.
- The use of **reductant coal** in TMC's pyrometallurgical processes, including both direct and indirect emissions, contributes approximately 0.26 kg CO_2 eq., making up 21% of the total climate change impact.
- There is a credit of 0.0019 kg CO_2 eq from the converter slag included in the 'other' bar.

7.1.1.2 Pyrometallurgy in Japan

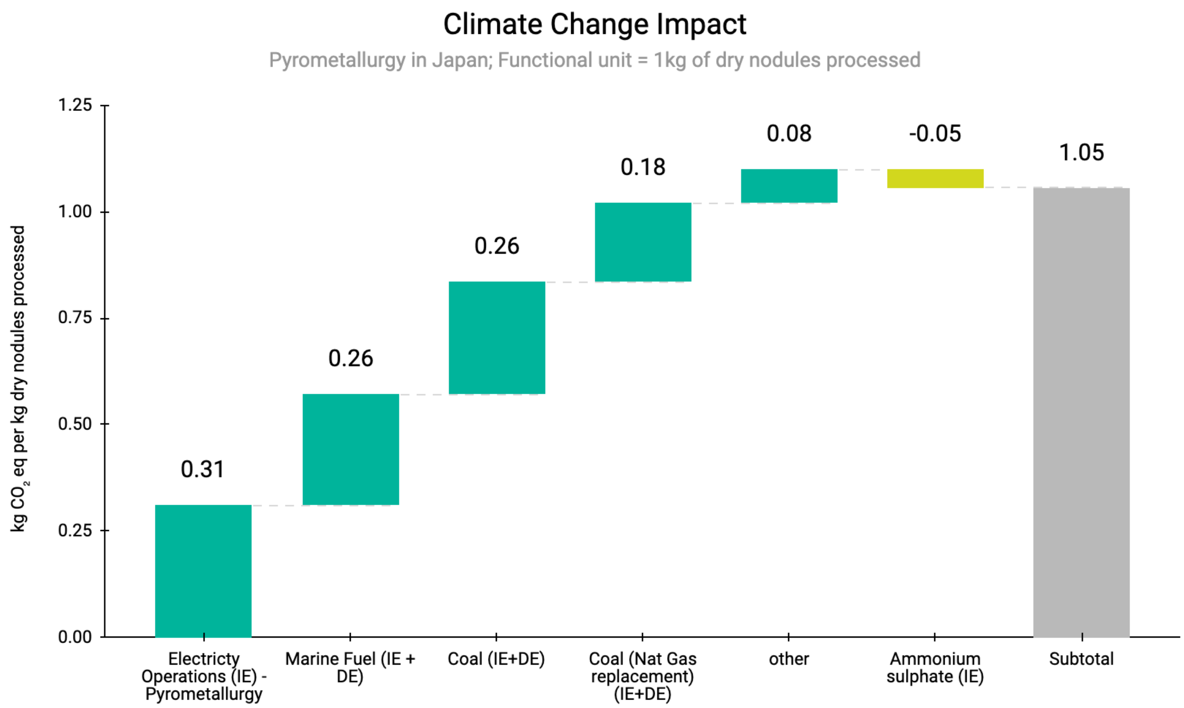

Figure 13: Climate Change Contribution Analysis for the Processing of 1kg of Dry Nodules (with Pyrometallurgy in Japan).

When pyrometallurgical processing is conducted in Japan, the total climate change impact amounts to 1.05 kg CO_2 eq. per kg dry nodule processed. The primary contributors to this impact are:

- **Electricity** use in Japan's pyrometallurgical operations contributes approximately 0.31 kg CO_2 eq., representing 30% of the total climate impact. This lower contribution compared to Indonesia reflects Japan's less carbon-intensive energy mix.
- **Marine fuel** usage during offshore operations and transshipment contributes approximately 0.26 kg CO_2 eq., or 25% of the total climate impact. Although the transportation distance to Japan is longer, the difference in fuel consumption compared to Indonesia is minimal.

- The use of **reductant coal** in TMC's pyrometallurgical process, including both direct and indirect emissions, contributes 0.26 kg CO_2 eq., making up 25% of the total climate change impact. This contribution remains consistent across both scenarios.
- There is a credit of 0.0019 kg CO_2 eq from the converter slag included in the 'other' bar.

7.1.2. Functional unit: 1kg Ni-Cu-Co matte (40.7% Ni, 30.5% Cu, 3.4% Co,)

This section presents the climate change impact associated with producing 1kg of Ni-Cu-Co matte under two scenarios: one where pyrometallurgical processing takes place in Indonesia and another where it occurs in Japan. The analysis includes emissions from offshore operations, transshipment, and pyrometallurgical activities, with detailed results for both scenarios illustrated in **Figure 14** (Indonesia) and **Figure 15** (Japan).

7.1.2.1 Pyrometallurgy in Indonesia

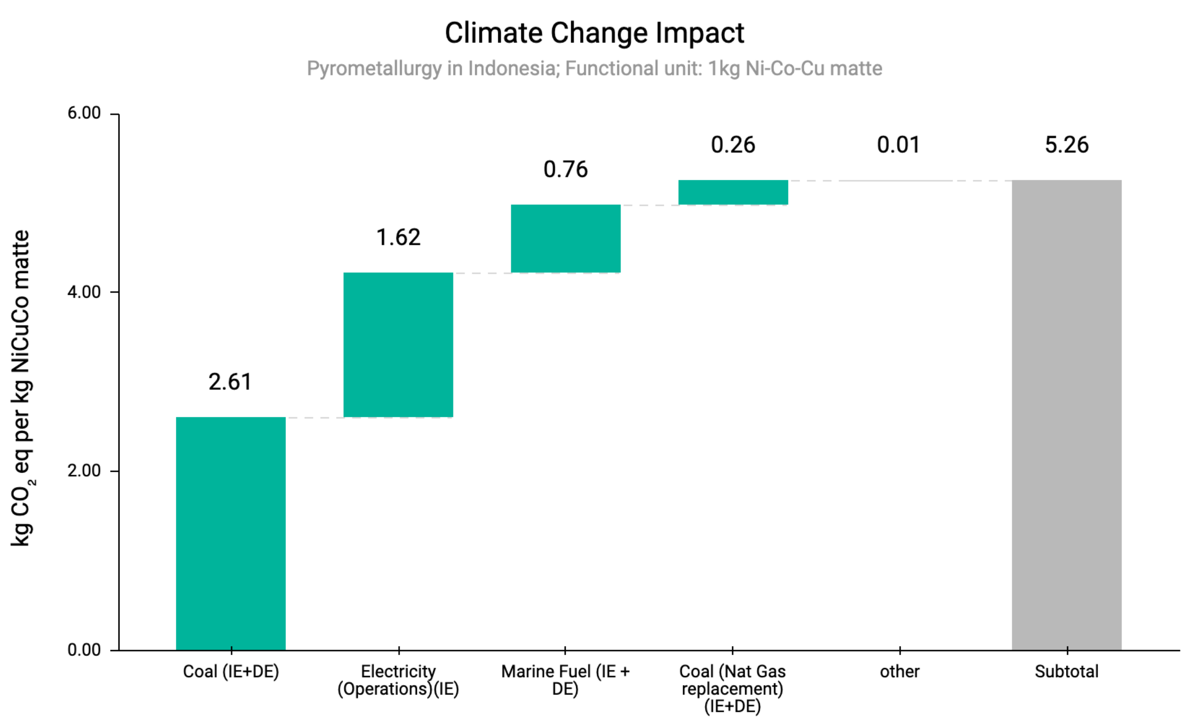

Figure 14: Climate Change Contribution Analysis for the Production of 1kg of Ni-Cu-Co matte (with Pyrometallurgy in Indonesia).

When pyrometallurgical processing is conducted in Indonesia, the total climate change impact amounts to 5.26 kg CO2 eq. per kg Ni-Cu-Co matte produced. The primary contributors to this impact are:

- **Reductant coal** use in TMC's pyrometallurgical operations (including both in direct and indirect emissions), contributing 2.61 kg CO2 eq. per kg Ni-Cu-Co matte, accounting for

50% of the total climate change impact. Coal is a key input in the smelting process, generating significant emissions.

- **Electricity** consumption in pyrometallurgical operations in Indonesia, contributing 1.62 kg CO_2 eq. per kg Ni-Cu-Co matte, or 31% of the total impact. The Indonesian energy grid, which is heavily reliant on fossil fuels, drives this high emission figure. However, electricity is not the dominant contributor because only 7.5% of the total electricity consumption is allocated to Ni-Cu-Co matte production; the majority is used for producing $MnSiO_3$.

- **Marine fuel** consumption by vessels during offshore operations contributing 0.76 kg CO_2 eq. per kg Ni-Cu-Co matte, accounting for 14% of the total climate change impact. This impact stems from the use of marine fuel oil for transportation.

- There is a credit of 0.059 kg CO_2 eq from the converter slag included in the 'other' bar.

7.1.2.2 Pyrometallurgy in Japan

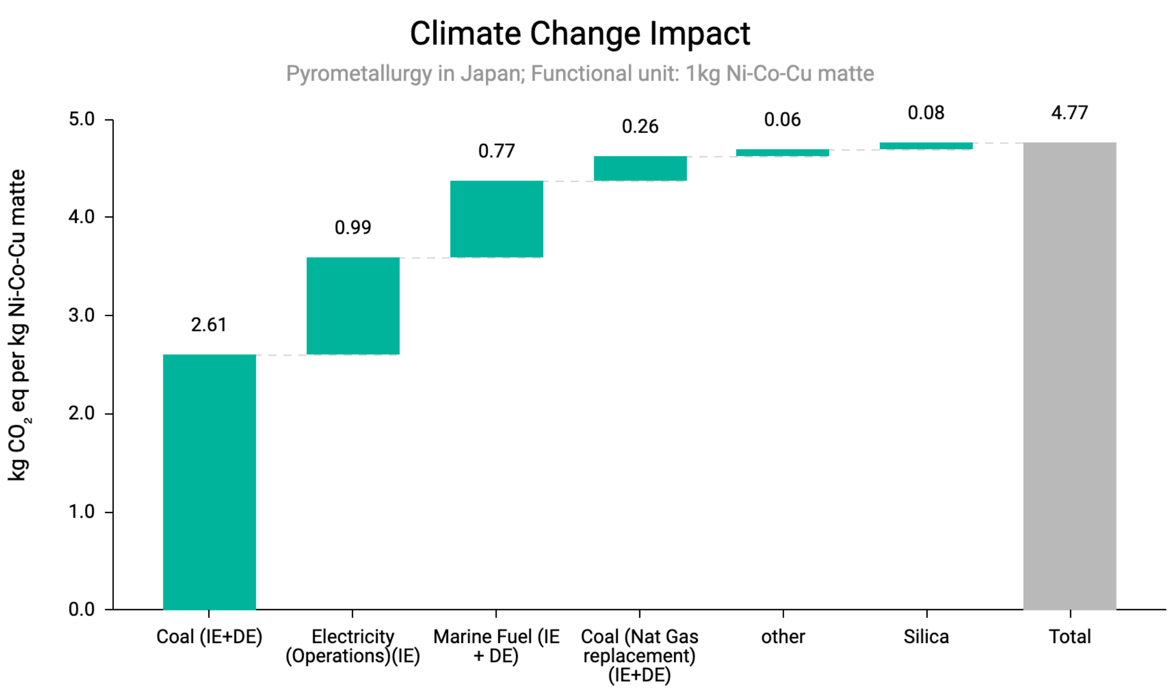

Figure 15: Climate Change Contribution Analysis for the production of 1kg of Ni-Cu-Co matte (with Pyrometallurgy in Japan).

When pyrometallurgical processing is conducted in Japan, the total climate change impact amounts to 4.77 kg CO_2 eq. per kg Ni-Cu-Co matte produced. The primary contributors to this impact are:

- **Reductant coal** use in pyrometallurgical operations in Japan contributing 2.61 kg CO_2 eq. per kg Ni-Cu-Co matte, representing 55% of the total climate impact. This figure remains consistent with the Indonesian scenario due to the similar coal requirements in both locations.
- **Electricity** use in Japan's pyrometallurgical operations contributes 0.99 kg CO_2 eq. per kg Ni-Cu-Co matte, or 21% of the total climate impact. Japan's less carbon-intensive energy grid reduces the overall contribution from electricity compared to Indonesia.
- **Marine fuel** consumption during offshore operations contributes 0.77 kg CO_2 eq. per kg Ni-Cu-Co matte, accounting for 16% of the total impact. Although the transport distance to Japan is greater than to Indonesia, the difference in fuel consumption is minimal.
- There is a credit of 0.059 kg CO_2 eq from the converter slag included in the 'other' bar.

7.1.3. Functional unit: 1kg Mn in TMC's $MnSiO_3$ (40% Mn)

This section presents the climate change impact associated with producing 1kg of Mn contained in TMC's $MnSiO_3$ under two scenarios: one where pyrometallurgical processing takes place in Indonesia and another where it occurs in Japan. The analysis includes emissions from offshore operations, transshipment, and pyrometallurgical activities, with detailed results for both scenarios illustrated in **Figure 16** (Indonesia) and **Figure 17** (Japan).

7.1.3.1 Pyrometallurgy in Indonesia

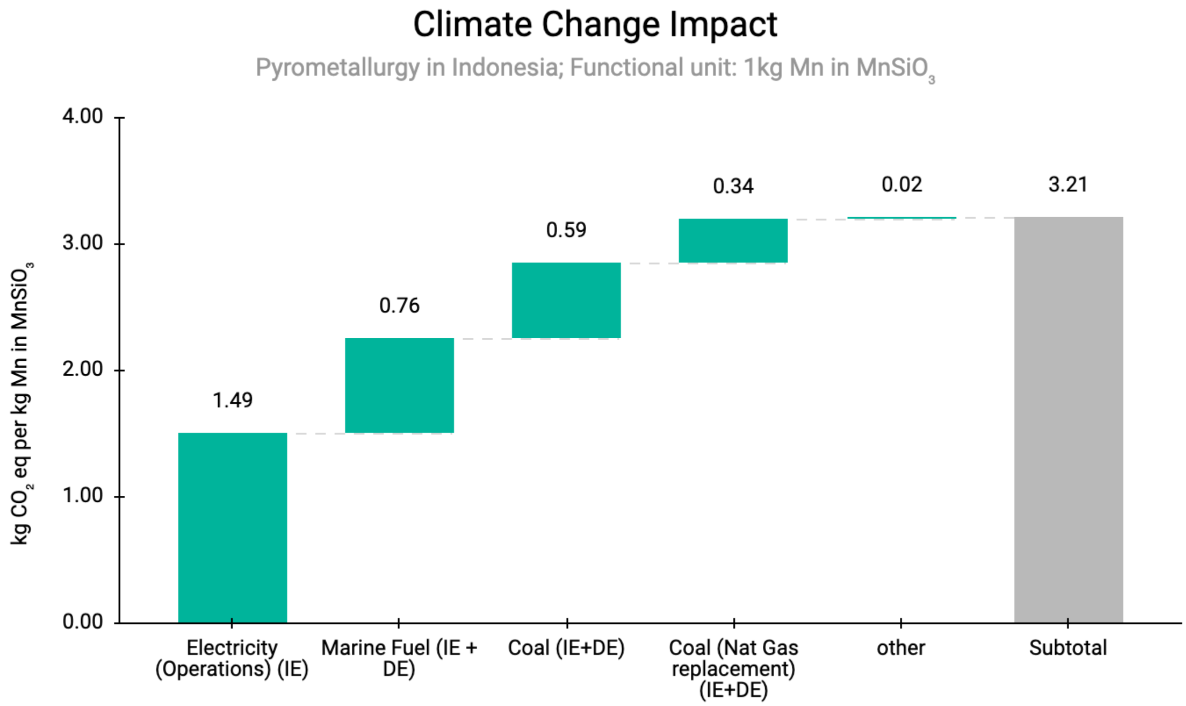

Figure 16: Climate Change Contribution Analysis for $MnSiO_3$ Production (with Pyrometallurgy in Indonesia).

When pyrometallurgical processing is conducted in Indonesia, the total climate change impact amounts to 3.21 kg CO_2 eq. per kg Mn in $MnSiO_3$ produced. The primary contributors to this impact are:

- **Electricity** usage during TMC's pyrometallurgical process in Indonesia contributes 1.49 kg CO_2 eq., representing 46% of the total climate change impact. This high contribution is largely due to the fossil fuel-heavy composition of Indonesia's energy grid.
- **Marine Fuel** consumption by vessels used during offshore operations and transshipment accounts for 0.76 kg CO_2 eq., or 24% of the total impact. This is primarily the result of burning marine fuel oil, which has a significant carbon footprint.
- The use of **coal** as a **reductant** in TMC's pyrometallurgical process contributes 0.59 kg CO_2 eq., or 18% of the total climate impact. This figure includes both direct emissions from coal combustion and indirect emissions related to coal processing.

7.1.3.2 Pyrometallurgy in Japan

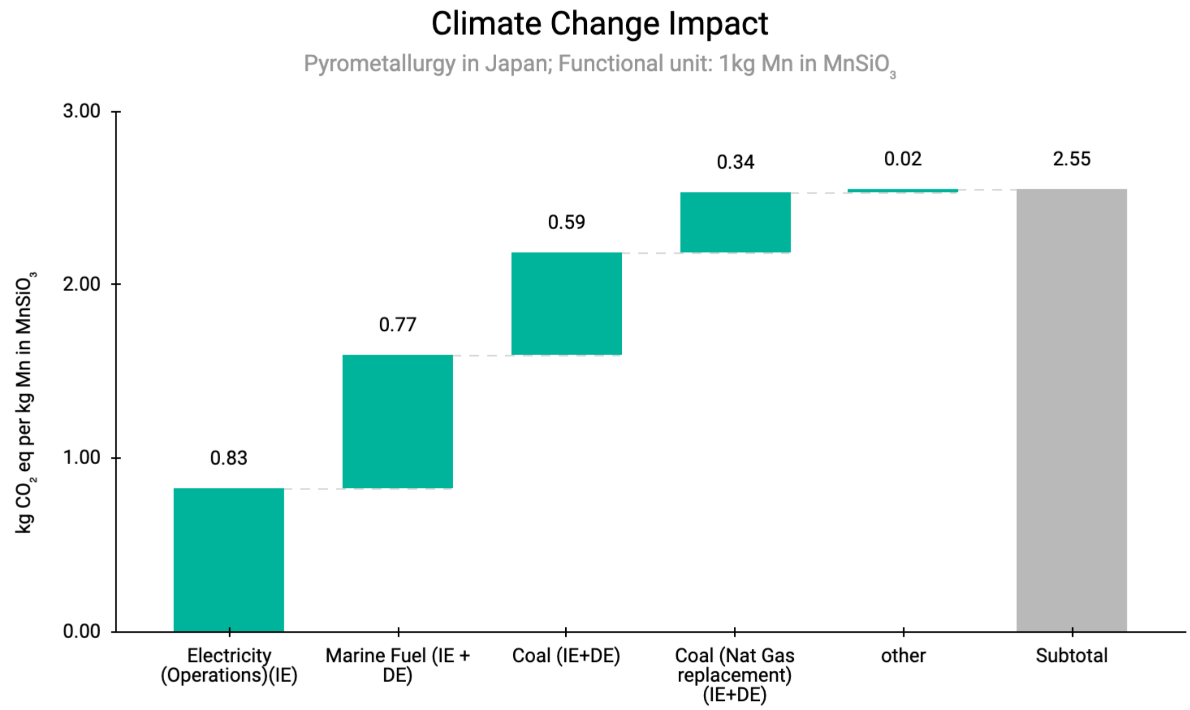

Figure 17: Climate Change Contribution Analysis for $MnSiO_3$ Production (with Pyrometallurgy in Japan).

When pyrometallurgical processing is carried out in Japan, the total climate change impact is reduced to 2.55 kg CO_2 eq. per kg Mn in $MnSiO_3$ produced. The top three most significant contributors are:

- **Electricity** usage in Japan's pyrometallurgical processes contributes 0.83 kg CO_2 eq., or 33% of the total climate impact. This lower contribution compared to Indonesia reflects Japan's less carbon-intensive energy grid.
- The impact from **marine fuel** use in offshore operations and transshipment amounts to 0.77 kg CO_2 eq., accounting for 30% of the total impact. Although the longer transportation distance to Japan results in slightly higher marine fuel consumption than in the Indonesian scenario, the difference is minimal.
- The use of **reductant coal** used in Japan's pyrometallurgical process contributes 0.59 kg CO_2 eq., or 23% of the total climate change impact. The contribution remains consistent due to the similar coal requirements in both locations.

7.1.4. Functional unit: 1kg Ni in NiSO4·6H2O (22.4% Ni)

This section presents the climate change impact associated with producing 1kg of Ni contained in $NiSO_4{\cdot}6H_2O$ under two scenarios: one where pyrometallurgical processing takes place in Indonesia and another where it occurs in Japan. The analysis includes emissions from offshore operations, transshipment, pyrometallurgical and hydrometallurgical activities, with detailed results for both scenarios illustrated in **Figure 18** (Indonesia) and **Figure 19** (Japan).

7.1.4.1 Pyrometallurgy in Indonesia

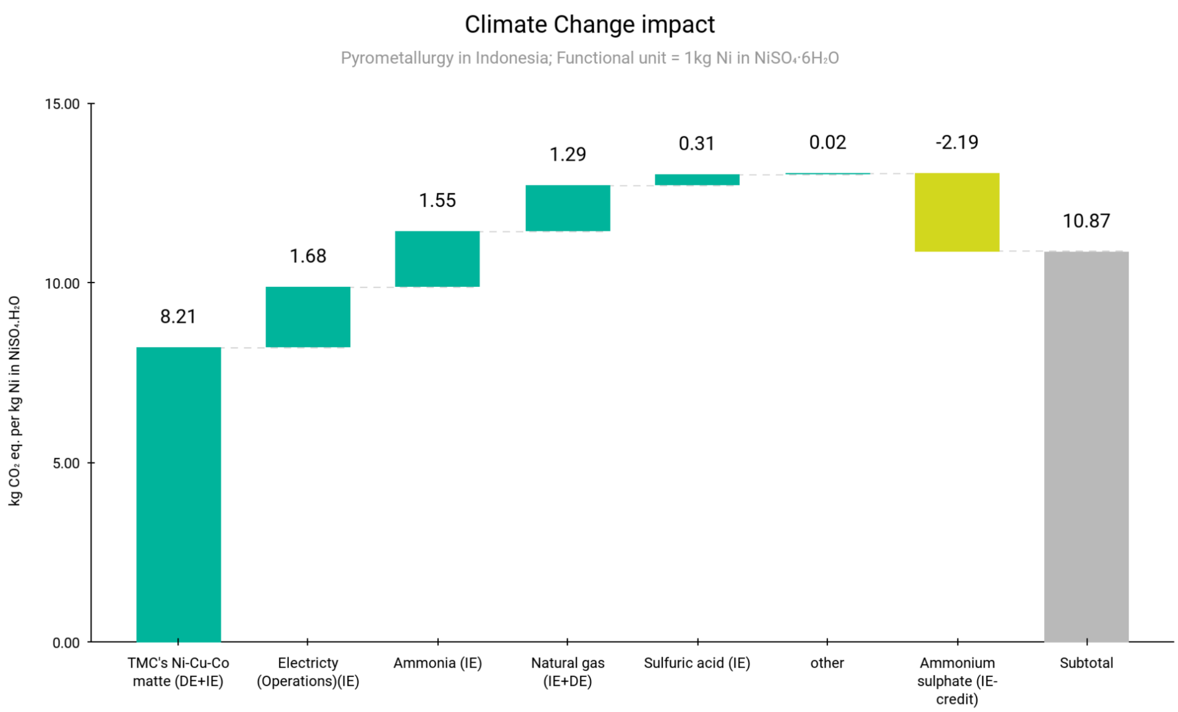

Figure 18: Climate Change Contribution Analysis for $NiSO_4{\cdot}6H_2O$ Production (with Pyrometallurgy in Indonesia).

When pyrometallurgical processing is conducted in Indonesia, the total climate change impact amounts to 10.87 kg CO_2 eq. per kg nickel in $NiSO_4{\cdot}6H_2O$ produced. The greatest contribution comes from the input of the Ni-Cu-Co matte from the pyrometallurgy process in Indonesia, contributing 8.21 kg CO_2 eq per kg nickel in $NiSO_4{\cdot}6H_2O$ representing 76% of total climate change impact (**Impact contribution breakdown of matte:** *14.6% is from Marine fuel, 49.9% from reductant coal, 5.03% from coal for natural gas replacement, 30.9% from electricity operations,* *and -1.79% from the converter slag, remaining is from 'other'*). Excluding the upstream emissions associated with Ni-Cu-Co matte production, the top contributors are:

- Credit from **ammonium sulfate** production which contributes -2.19 kg CO_2 eq. per kg Ni in $NiSO_4 \cdot 6H_2O$, which reduces the overall climate impact.
- **Electricity** usage during TMC's hydrometallurgical operations which contributes 1.68 kg CO_2 eq. per kg Ni in $NiSO_4 \cdot 6H_2O$, or 15.5% of the total climate change impact. The emissions stem from the fossil-fuel-heavy energy grid in Indonesia.
- **Liquid ammonia** required for the iron removal step which contributes 1.55 kg CO_2 eq. per kg Ni in $NiSO_4 \cdot 6H_2O$, accounting for 14.2% of the total climate change impact. This input is essential for removing impurities during processing.

7.1.4.2 Pyrometallurgy in Japan

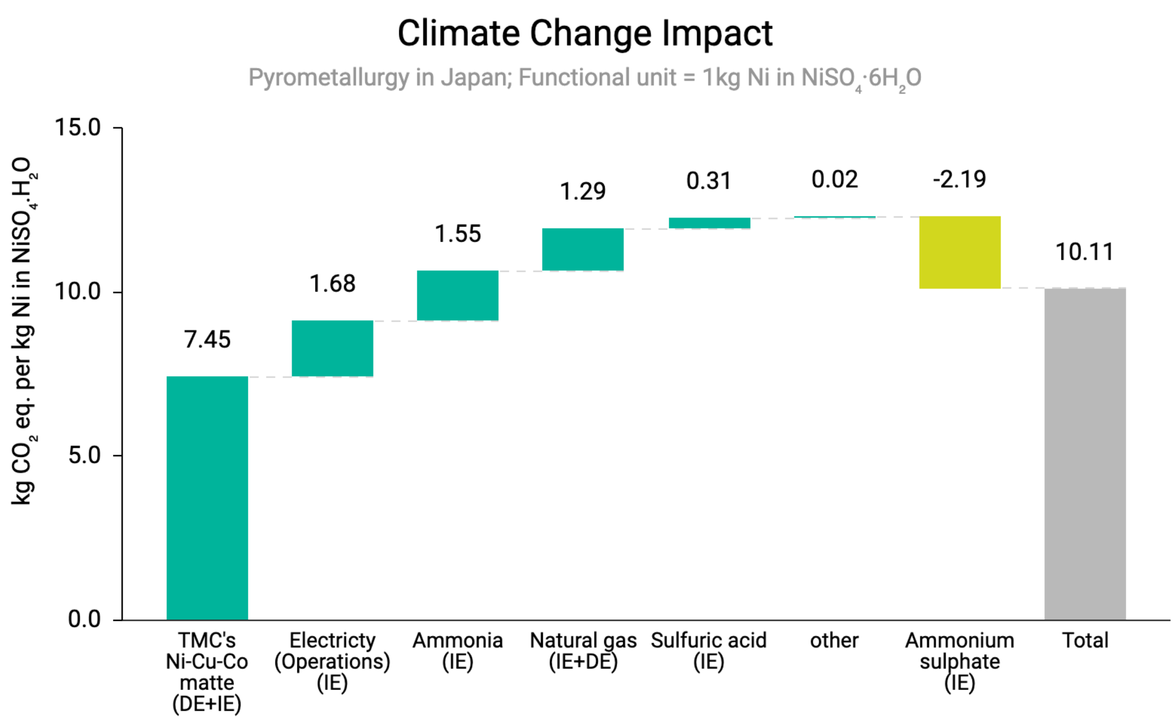

Figure 19: Climate Change Contribution Analysis for $NiSO_4 \cdot 6H_2O$ Production (with Pyrometallurgy in Japan).

When pyrometallurgical processing is conducted in Japan, the total climate change impact is slightly lower, amounting to 10.11 kg CO_2 eq per kg Ni in $NiSO_4{\cdot}6H_2O$ produced. The largest contributor remains the input of Ni-Cu-Co matte from the pyrometallurgical process, which contributes 7.45 kg CO_2 eq. per kg Ni in $NiSO_4{\cdot}6H_2O$, representing 74% of the total climate change impact (**impact contribution breakdown of matte:** *16.7% is from marine fuel, 56.6% from reductant coal, 5.7% from coal for natural gas replacement, 21.5% from electricity operations, and -2.03% from the converter slag, the remaining is from 'other'*).

Excluding upstream emissions from Ni-Cu-Co matte production, the primary contributors are:

- Credit from **ammonium sulfate** production contributing -2.19 kg CO_2 eq. per kg Ni in $NiSO_4{\cdot}6H_2O$, reducing the overall environmental burden.
- **Electricity** usage during TMC's hydrometallurgical operations contributes 1.68 kg CO_2 eq. per kg Ni in $NiSO_4{\cdot}6H_2O$, representing 17% of the total climate change impact. Japan's less carbon-intensive energy grid helps slightly mitigate the impact from electricity usage compared to Indonesia.
- **Liquid ammonia** used in the iron removal step which contributes 1.55 kg CO_2 eq. per kg Ni in $NiSO_4{\cdot}6H_2O$, accounting for 15% of the total climate change impact, similar to the Indonesian scenario.

7.1.5. Functional unit: 1kg Co in CoSO4·7H2O (21.0% Co)

This section presents the climate change impact associated with producing 1kg of Co contained in $CoSO_4{\cdot}7H_2O$ under two scenarios: one where pyrometallurgical processing takes place in Indonesia and another where it occurs in Japan. The analysis includes emissions from offshore operations, transshipment, pyrometallurgical and hydrometallurgical activities, with detailed results for both scenarios illustrated in **Figure 20** (Indonesia) and **Figure 21** (Japan).

7.1.5.1: Pyrometallurgy in Indonesia

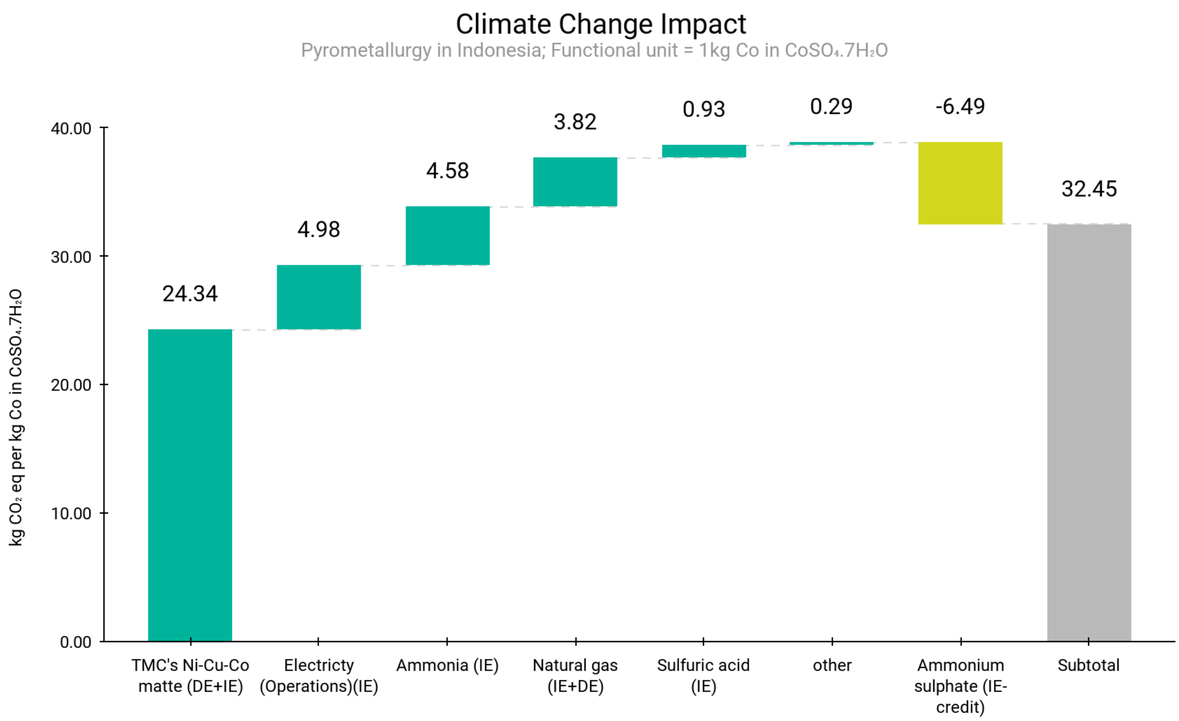

Figure 20: Climate Change Contribution Analysis for $CoSO_4{\cdot}7H_2O$ Production (with Pyrometallurgy in Indonesia).

When pyrometallurgical processing is conducted in Indonesia, the total climate change impact amounts to 32.45 kg CO_2 eq. per kg Co in $CoSO_4{\cdot}7H_2O$ produced. The greatest contribution comes from the input of the Ni-Cu-Co matte from the pyrometallurgy process in Indonesia, contributing 24.34 kg CO_2 eq per kg Co in $CoSO_4{\cdot}7H_2O$, 75% of total impact (**impact contribution breakdown of matte:** *15.6% is from marine fuel, 56.7% from reductant coal, 5.3% from coal for natural gas replacement, 32.6% from electricity operations, and -7.98% from the converter slag, the* *remaining is from 'other'*). Excluding the upstream emissions associated with Ni-Cu-Co matte production, the top contributors are:

- Credit from **ammonium sulfate** production, which contributes -6.49 kg CO_2 eq. per kg Co in $CoSO_4{\cdot}7H_2O$.
- **Electricity** usage during TMC's hydrometallurgical operations contributes 4.98 kg CO_2 eq. per kg Co in $CoSO_4{\cdot}7H_2O$, or 15% of the total climate change impact. The high emissions result from Indonesia's fossil-fuel-intensive energy grid.
- **Liquid ammonia** required for the solvent extraction process which contributes 4.58 kg CO_2 eq. per kg Co in $CoSO_4{\cdot}7H_2O$, accounting for 14% of the total climate change impact. Liquid ammonia is a key input in the extraction process, adding to the overall emissions.

7.1.5.2 Pyrometallurgy in Japan

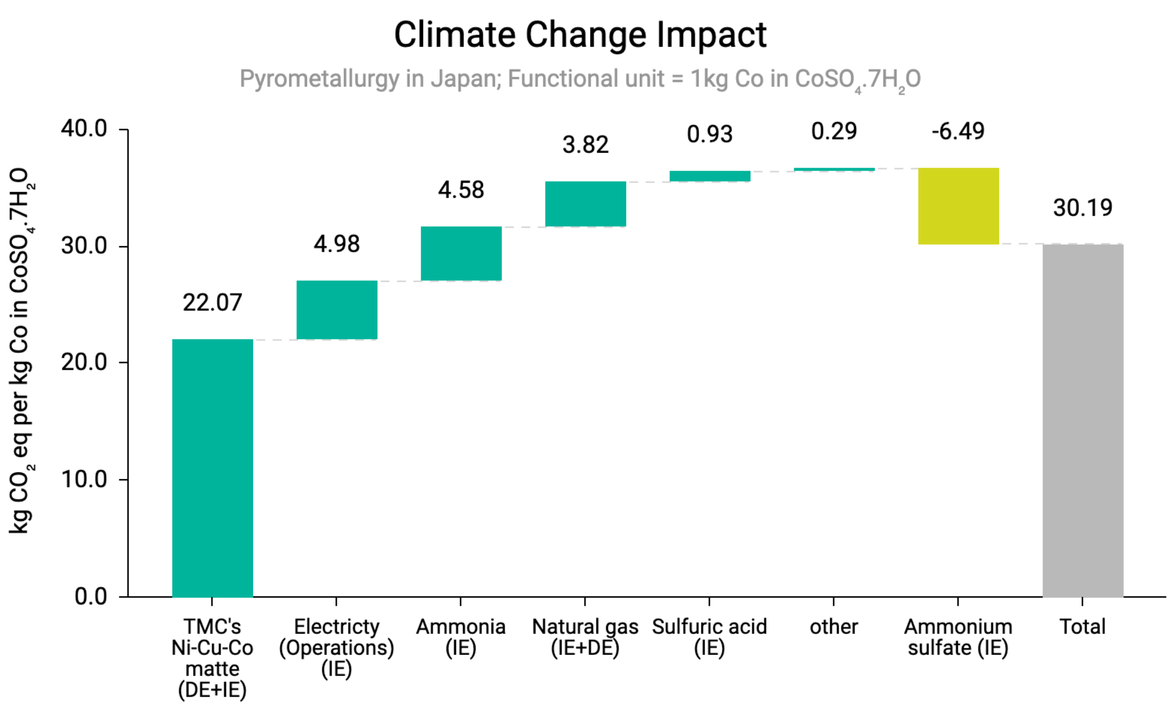

Figure 21: Climate Change Contribution Analysis for $CoSO_4{\cdot}7H_2O$ Production (with Pyrometallurgy in Japan).

- When pyrometallurgical processing occurs in Japan, the total climate change impact decreases slightly to 30.19 kg CO_2 eq. per kg Co in $CoSO_4{\cdot}7H_2O$ produced. The largest contributor remains the input of Ni-Cu-Co matte from the pyrometallurgical process, which contributes 22.07 kg CO_2 eq per kg Co in $CoSO_4{\cdot}7H_2O$, or 73% of the total impact (***impact contribution breakdown of matte:*** *17.8% is from marine fuel, 60.4% from* *reductant coal, 6.1% from coal for natural gas replacement, 22.9% from electricity operations, and -8.9% from the converter slag, the remaining is from 'other'*). Excluding upstream emissions from Ni-Cu-Co matte production, the main contributors are:

1. Credit from **ammonium sulfate** production which contributes -6.49 kg CO_2 eq. per kg Co in $CoSO_4 \cdot 7H_2O$, reducing the overall climate impact.
2. **Electricity** consumption in TMC's hydrometallurgical operations contributes 4.98 kg CO_2 eq. per kg Co in $CoSO_4 \cdot 7H_2O$, accounting for 16% of the total climate change impact. The less carbon-intensive Japanese grid results in slightly lower electricity-related emissions compared to Indonesia.
3. **Liquid ammonia** required for solvent extraction which contributes 4.58 kg CO_2 eq. per kg Co in $CoSO_4 \cdot 7H_2O$, making up 15% of the total impact, similar to the contribution in Indonesia.

7.1.6. Functional unit: 1kg copper cathode (99.99% Cu)

This section presents the climate change impact associated with producing 1kg of copper cathode under two scenarios: one where pyrometallurgical processing takes place in Indonesia and another where it occurs in Japan. The analysis includes emissions from offshore operations, transshipment, pyrometallurgical and hydrometallurgical activities, with detailed results for both scenarios illustrated in **Figure 22** (Indonesia) and **Figure 23** (Japan).

7.1.6.1 Pyrometallurgy in Indonesia

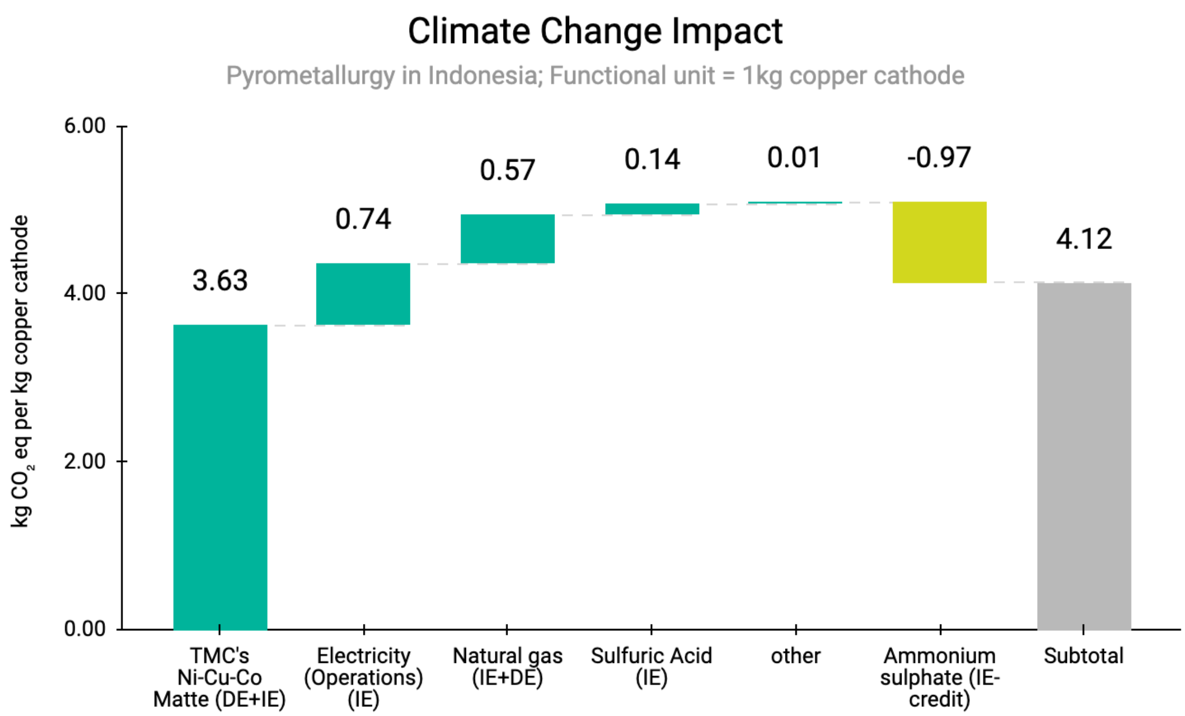

Figure 22: Climate Change Contribution Analysis for Copper Cathode Production (with Pyrometallurgy in Indonesia).

When pyrometallurgical processing is conducted in Indonesia, the total climate change impact amounts to 4.12 kg CO_2 eq. per kg copper cathode produced. The largest contributor to this impact is the input of Ni-Cu-Co matte from the pyrometallurgical process, which contributes 3.63 kg CO_2 eq. per kg copper cathode, or 88% of the total climate change impact (***impact contribution breakdown of matte:*** *15.2% is from marine fuel, 51.6% from reductant coal, 5.2% from coal for natural gas replacement, 32% from electricity operations, and -5.6% from the* *converter slag, the remaining is from 'other'*). Excluding upstream emissions from Ni-Cu-Co matte production, the key contributors are:

- Credit for **ammonium sulfate** production, with a contribution of -0.97 kg CO_2 eq. per kg of copper cathode.
- **Electricity** used in TMC's hydrometallurgical operations, contributing 0.74 kg CO_2 eq. per kg copper cathode, which accounts for 18% of the total climate change impact. This is largely driven by the fossil-fuel-intensive Indonesian energy grid.
- **Natural gas** consumption during various stages of the hydrometallurgical process (including both direct and indirect emissions), contributing approximately 0.57 kg CO_2 eq. per kg copper cathode, or 14% of the total climate change impact. Natural gas is used in various stages of the hydrometallurgical process.

7.1.6.2 Pyrometallurgy in Japan

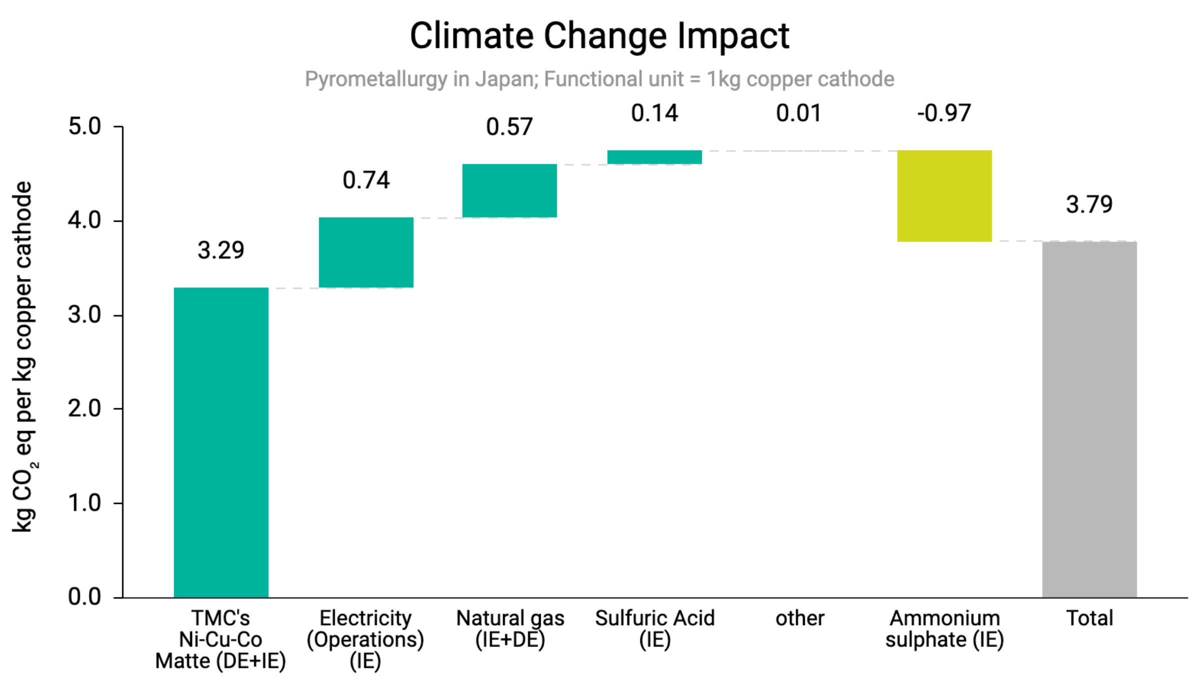

Figure 23: Climate Change Contribution Analysis for Copper Cathode Production (with Pyrometallurgy in Japan).

When pyrometallurgical processing is conducted in Japan, the total climate change impact decreases to 3.79 kg CO_2 eq. per kg copper cathode produced. As with Indonesia, the largest contribution comes from the input of Ni-Cu-Co matte from the pyrometallurgical process, which contributes 3.29 kg CO_2 eq. per kg copper cathode, representing 87% of the total climate change impact (*impact contribution breakdown of matte: 17.4% is from marine fuel, 59.0% from reductant coal, 6.0% from coal for natural gas replacement, 22.4% from electricity operations, and -6.4% from the converter slag, the remaining is from 'other'*). Excluding upstream emissions from Ni-Cu-Co matte production, the top contributors are:

1. Credit from **ammonium sulfate** production contributing -0.97 kg CO_2 eq. per kilogram of copper cathode, reducing the overall environmental burden.
2. **Electricity** consumption in TMC's hydrometallurgical operations which contributes 0.74 kg CO_2 eq. per kg copper cathode, accounting for 20% of the total climate change impact. Japan's less carbon-intensive grid helps mitigate the electricity-related emissions slightly compared to Indonesia.
3. **Natural gas** usage in hydrometallurgical operations (including both direct and indirect emissions), contributes approximately 0.57 kg CO_2 eq. per kg copper cathode, or 15% of the total impact. The natural gas requirements remain consistent between both scenarios.

7.1.7. Climate Change Scope Emissions

Climate change impact can be classified into scope 1, 2, and upstream scope 3 emissions (defined in **Section 4.8.1**). The impact broken down by scopes (1, 2 and 3) is presented in **Figure 24** (for the processing of 1kg of dry nodules), **Figure 25** (for the production of $MnSiO_3$), **Figure 26** (for the production of Ni-Cu-Co matte), **Figure 27** (for the production of copper cathode), **Figure 28** ($CoSO_4{\cdot}7H_2O$) and **Figure 29** ($NiSO_4{\cdot}6H_2O$). It should be noted that the scope 3 emissions for copper cathode are negative due to the credit received from the ammonium sulfate outweighing the impacts from the reagents and energy used in producing copper cathode. This is because a relatively large volume of ammonium sulfate is produced.

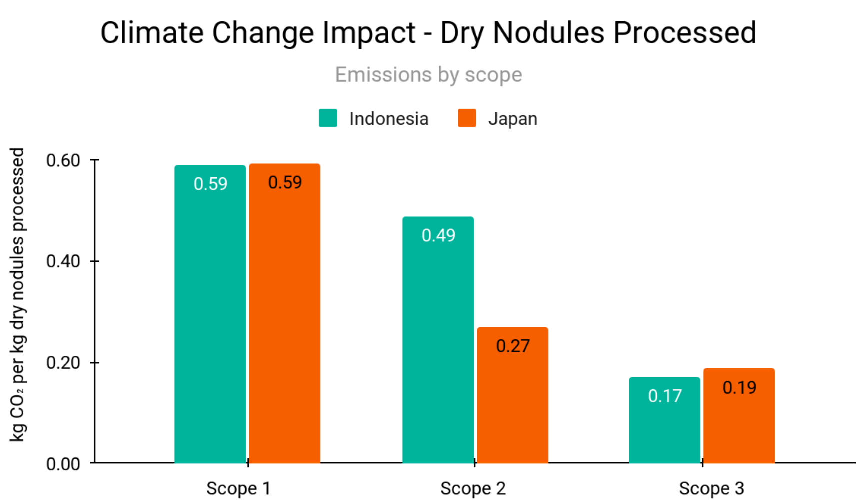

Figure 24: Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the collection and processing of 1kg of dry nodules, when Pyrometallurgy is performed in Indonesia or Japan.

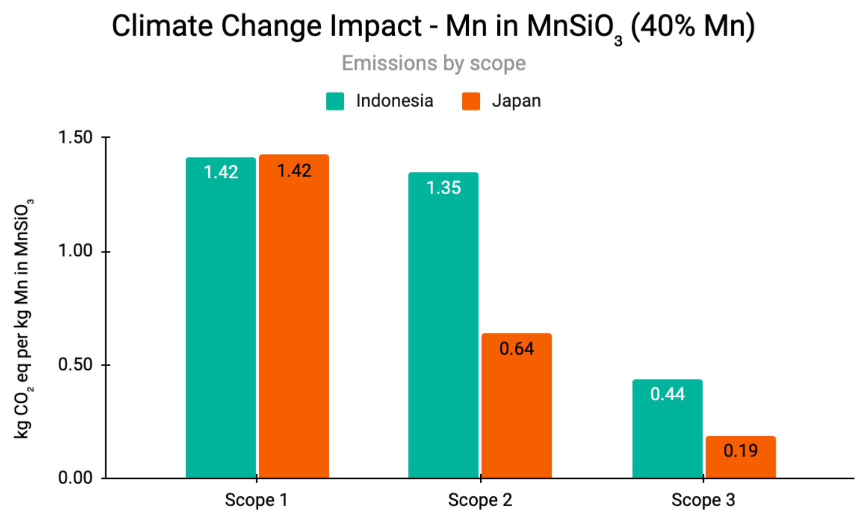

Figure 25: Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of$MnSiO_3$, When Pyrometallurgy is performed in Indonesia or Japan.

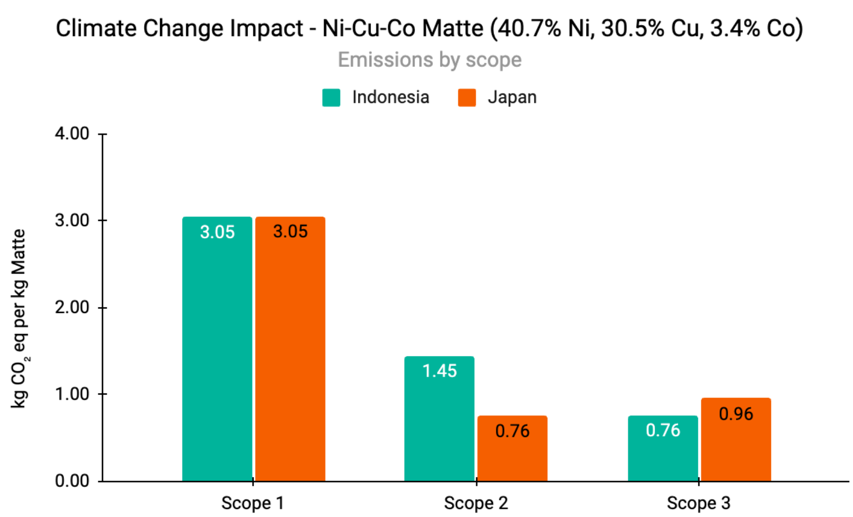

Figure 26: Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of Ni-Cu-Co matte, when Pyrometallurgy is performed in Indonesia or Japan.

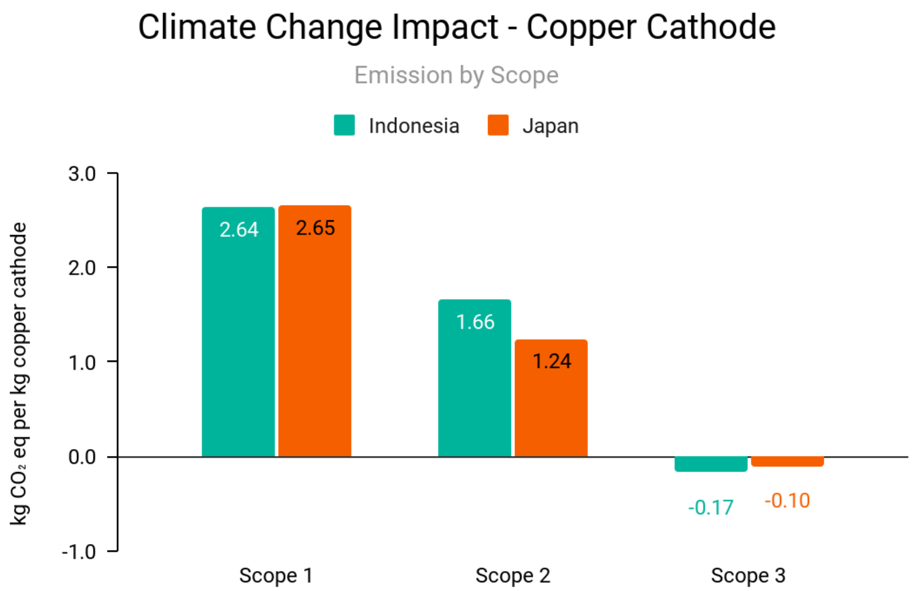

Figure 27: Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of Copper Cathode, When Pyrometallurgy is performed in Indonesia or Japan.

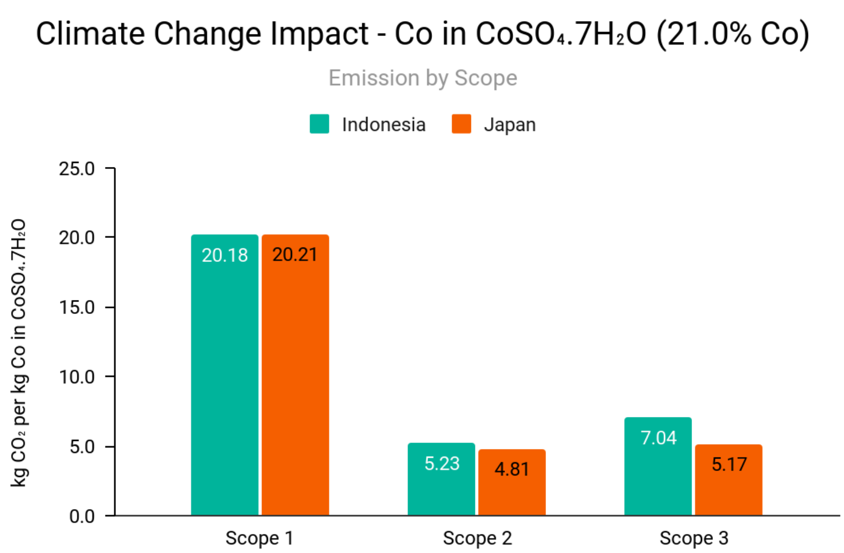

Figure 28: Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of $CoSO_4 \cdot 7H_2O$, When Pyrometallurgy is performed in Indonesia or Japan.

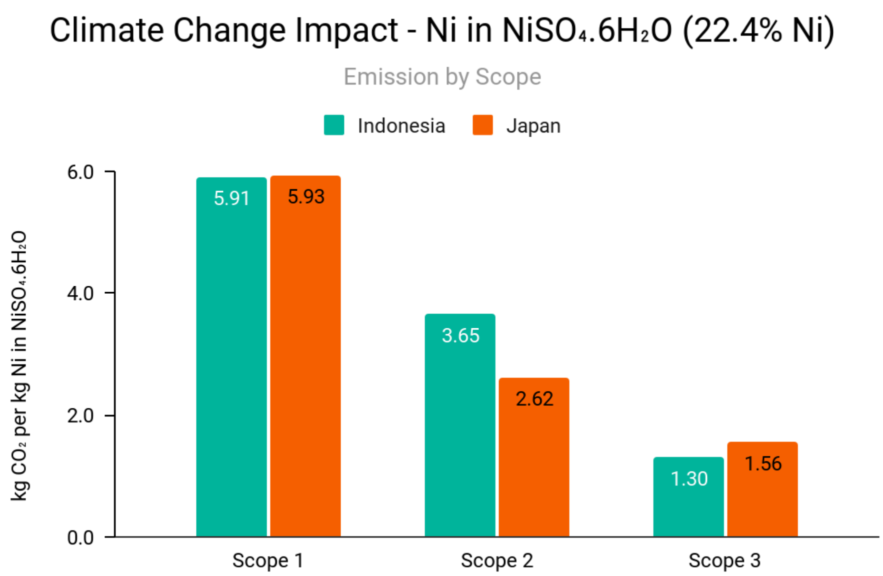

Figure 29: Climate Change Contribution Analysis by Scope of Emissions, Specifically Associated with the Production of $NiSO_4 \cdot 6H_2O$, When Pyrometallurgy is performed in Indonesia or Japan.

The key drivers for Scope 1, Scope 2, and Scope 3 emissions are consistent across these products. Scope 1 emissions primarily stem from direct emissions, including the combustion of coal used in pyrometallurgy, natural gas used in hydrometallurgy, and emissions from marine fuel burned during offshore operations. Scope 2 emissions result from the indirect emissions associated with electricity consumption during both the pyrometallurgy and hydrometallurgy stages. Scope 3 emissions capture the upstream impacts related to the production of fuels and reagents, such as natural gas and coal, that are critical for both hydrometallurgical and pyrometallurgical processing as well as the credits received from the system expansion of ammonium sulfate and the converter slag.

7.1.8. Other Impact Categories

The results for the additional environmental impact categories for each functional unit are provided in **Appendix C**. The impacts are broken down by offshore operations, TMC's pyrometallurgy process and TMC's hydrometallurgy process.

8. Life Cycle Interpretation

The results have been interpreted with reference to the goal and scope, comparing the impacts associated with the identified process routes, geographic regions, and technology implemented.

8.1. Sensitivity Analysis

A sensitivity analysis was conducted to explore how variations in key contributors affect the total climate change impacts associated with the final product. This analysis was further extended to evaluate the influence of different scenarios involving alternative sources of low-carbon and renewable electricity, which TMC could source in the future. The results of these sensitivity analyses are detailed in the following subsections.

8.1.1. Sensitivity to Alternative Sources of Low Carbon and Renewable Electricity

Additional sensitivity analysis was conducted to assess how climate change impacts vary based on alternative low-carbon and renewable electricity sources that TMC may utilise in the future through virtual power purchase agreements. Various permutations of the following scenarios were evaluated:

- Indonesian pyrometallurgy plant: Electricity mix comprising 25% solar and 75% coal combustion.
- Indonesian pyrometallurgy plant: 100% hydroelectricity.
- Japanese pyrometallurgy plant: 100% nuclear energy for electricity
- South Korean hydrometallurgy plant: 100% nuclear energy.

TMC is particularly interested in how these changes affect the total climate change impacts associated with the production of each of their products, and for processing the dried nodules. The results of this sensitivity analysis are presented in **Figure 30** (dry nodules processed), **Figure 31** ($MnSiO_3$), **Figure 32** (Ni-Cu-Co matte) **Figure 33** ($CoSO_4{\cdot}7H_2O$) and **Figure 34** ($NiSO_4{\cdot}6H_2O$).

Collection and processing of dry nodules

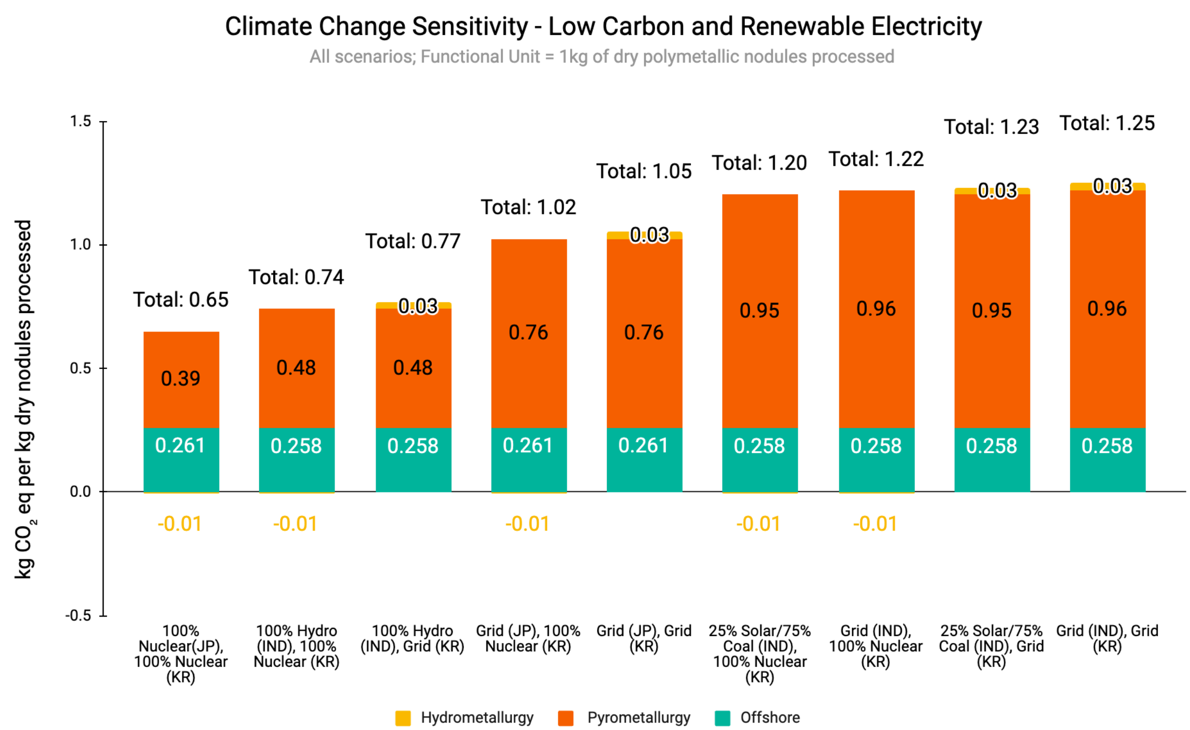

Figure 30: Sensitivity Analysis on the Variation in Global Warming Potential Impacts of processing the dry polymetallic nodules with the Application of Various Low Carbon and Renewable Electricity Mixes.

In all scenarios, pyrometallurgical processes contribute the most to the total climate change impacts. Emissions from offshore operations, which include shipping and transshipment, range between 0.258 kg CO_2 eq and 0.261 kg CO_2 eq per kg of dry nodules processed, depending on whether pyrometallurgy is conducted in Indonesia or Japan.

The best-case scenario, where pyrometallurgy in Japan and hydrometallurgy in South Korea both use nuclear energy, results in total emissions of 0.65 kg CO_2 eq per kg of dry nodules processed. In contrast, the worst-case scenario, which assumes grid electricity for both the pyrometallurgy in Indonesia and hydrometallurgy in South Korea, yields emissions of 1.25 kg CO_2 eq per kg of dry nodules processed. When nuclear energy is used in South Korea's hydrometallurgical plant, the impact from electricity decreases to a value such that the credit received from ammonium sulfate production results in an overall negative impact for hydrometallurgy.

Production of $MnSiO_3$

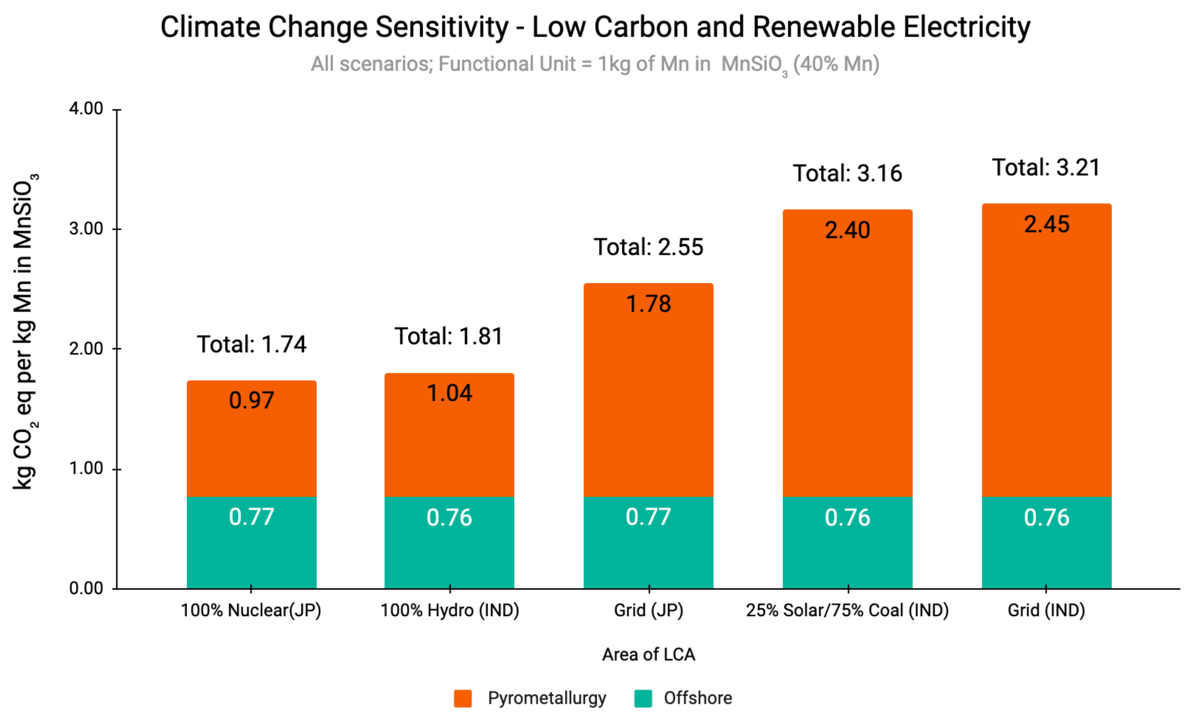

Figure 31: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for the production of $MnSiO_3$ with the Application of Various Low Carbon and Renewable Electricity Mixes.

In all scenarios, pyrometallurgical processes remain the top contributor to the total climate change impacts. Emissions from offshore operations, which include shipping and transshipment, range between 0.76 kg CO_2 eq and 0.77 kg CO_2 eq per kg of Mn in $MnSiO_3$, depending on whether pyrometallurgy is conducted in Indonesia or Japan.

The best-case scenario, where pyrometallurgy in Japan uses nuclear energy, results in total emissions of 1.74 kg CO_2 eq per kg of dry nodules processed. In contrast, the worst-case scenario, which assumes grid electricity for pyrometallurgy in Indonesia yields emissions of 3.21 kg CO_2 eq per kg Mn in $MnSiO_3$.

Production of Ni-Cu-Co Matte

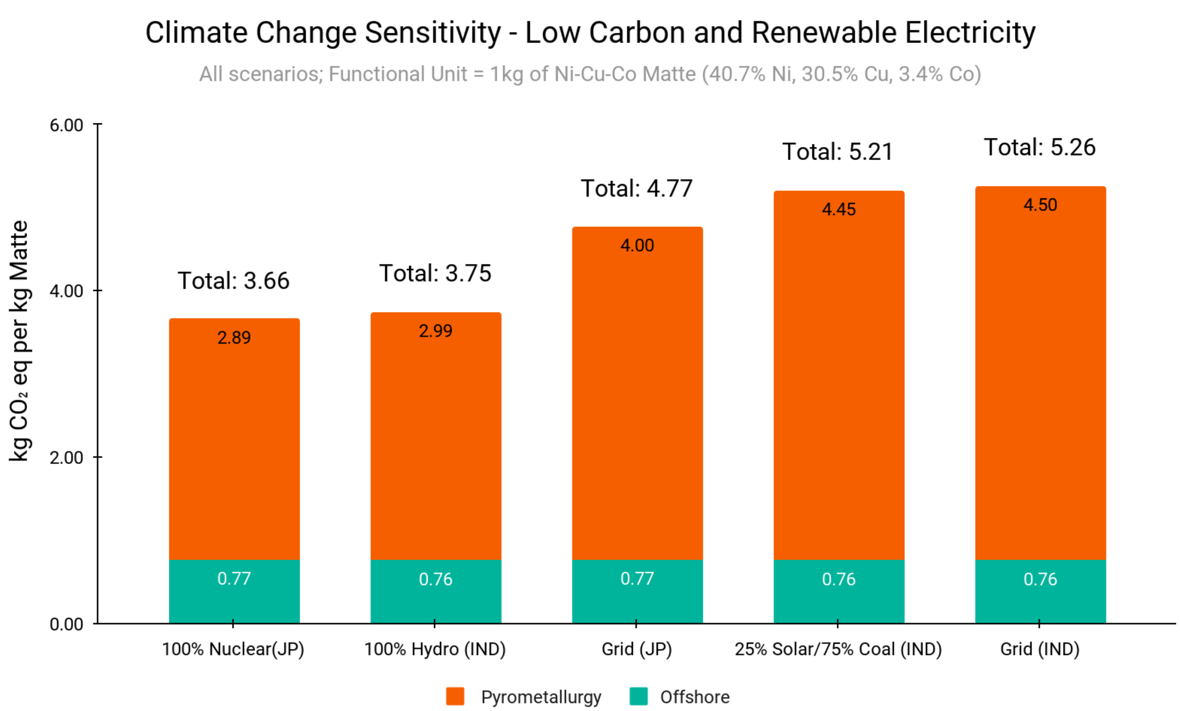

Figure 32: Sensitivity Analysis on the Variation in Global Warming Potential Impacts for production of Ni-Cu-Co matte with the Application of Various Low Carbon and Renewable Electricity Mixes.

In all scenarios, pyrometallurgical processes remain the top contributor to the total climate change impacts. Emissions from offshore operations, which include shipping and transshipment, range between 0.76 kg CO_2 eq and 0.77 kg CO_2 eq per kg of matte depending on whether pyrometallurgy is conducted in Indonesia or Japan.

The best-case scenario, where pyrometallurgy in Japan uses nuclear energy, results in total emissions of 3.66 kg CO_2 eq per kg ofmatte. In contrast, the worst-case scenario, which assumes grid electricity for pyrometallurgy in Indonesia yields emissions of 5.26 kg CO_2 eq per kg matte.

Production of copper cathode

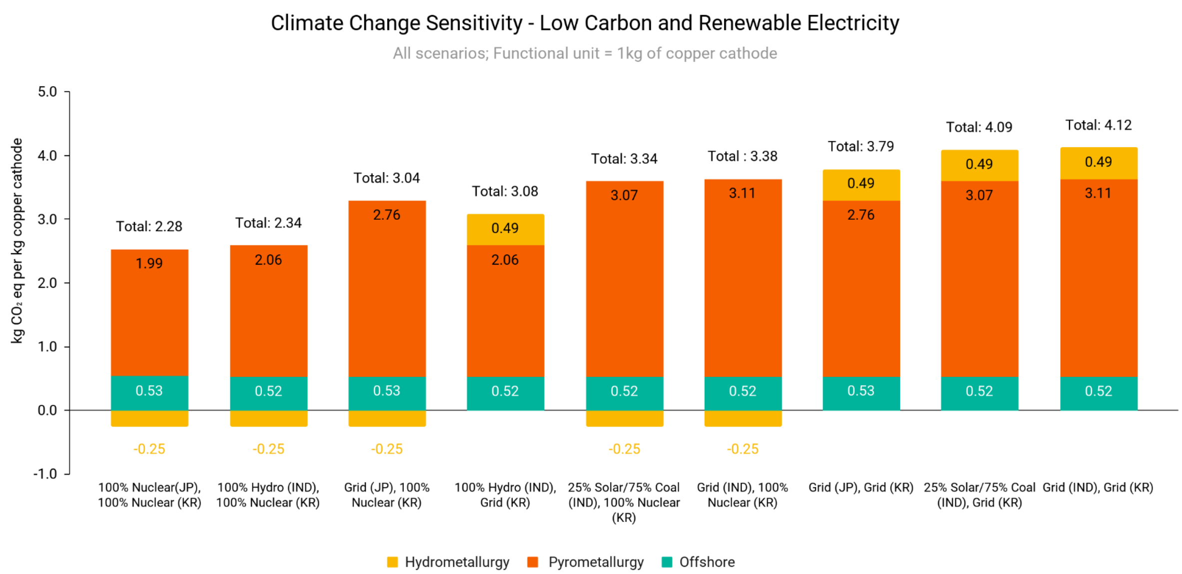

Figure 33: Sensitivity Analysis of the Variation in Global Warming Potential Impacts of Copper Cathode Production with the Application of Various Low Carbon and Renewable Electricity Mixes.

In all scenarios, pyrometallurgical processes remain the top contributor to the total climate change impacts. Emissions from offshore operations, which include shipping and transshipment, range between 0.52 kg CO_2 eq and 0.53 kg CO_2 eq per kg of copper cathode, depending on whether pyrometallurgy is conducted in Indonesia or Japan.

The best-case scenario, where pyrometallurgy in Japan and hydrometallurgy in South Korea both use nuclear energy, results in total emissions of 2.28 kg CO_2 eq per kg of copper cathode produced. In contrast, the worst-case scenario, which assumes grid electricity for both the pyrometallurgy in Indonesia and hydrometallurgy in South Korea, yields emissions of 4.12 kg CO_2 eq per kg of copper cathode. When nuclear energy is used in South Korea's hydrometallurgical plant, the impact from electricity decreases to a value such that the credit received from ammonium sulfate production results in an overall negative impact for hydrometallurgy.

Production of $CoSO_4 \cdot 7H_2O$

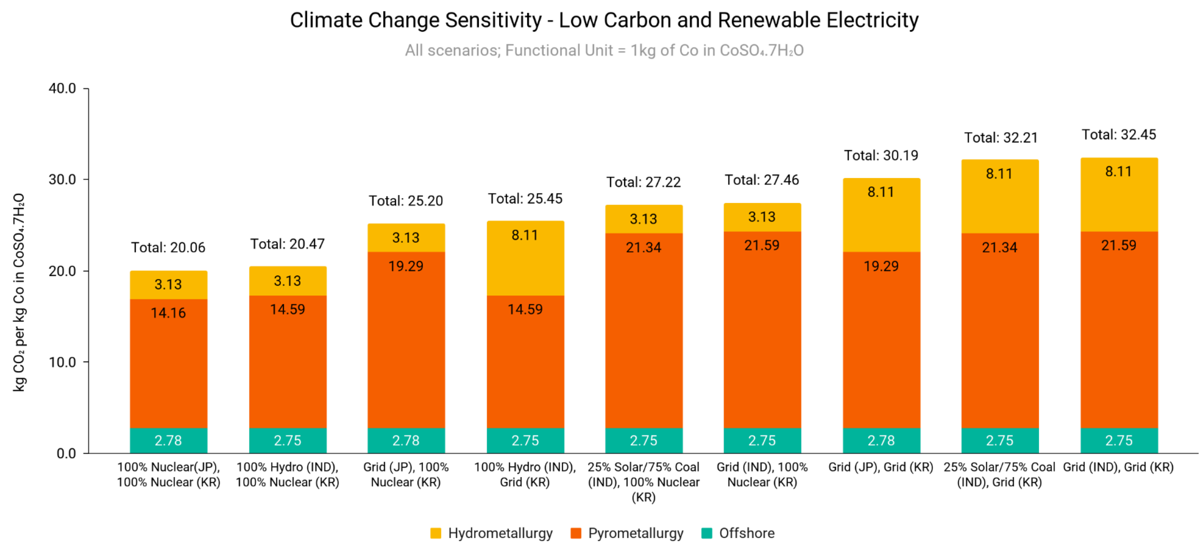

Figure 34: Sensitivity Analysis of the Variation in Global Warming Potential Impacts of $CoSO_4 \cdot 7H_2O$ Production with the Application of Various Low Carbon and Renewable Electricity Mixes.

As with copper cathode, pyrometallurgical processes are the largest contributors to climate change impacts in the production of $CoSO_4 \cdot 7H_2O$. Offshore emissions associated with shipping operations range between 2.75 kg CO_2 eq and 2.78 kg CO_2 eq per kg of Co in $CoSO_4 \cdot 7H_2O$, depending on the location of the pyrometallurgy process (Indonesia or Japan).

The best-case scenario involves using nuclear energy for both pyrometallurgy in Japan and hydrometallurgy in South Korea, leading to emissions of 20.06 kg CO_2 eq per kg of cobalt in $CoSO_4 \cdot 7H_2O$. Conversely, the worst-case scenario, which assumes grid electricity for both pyrometallurgy in Indonesia and hydrometallurgy in South Korea, results in 32.45 kg CO_2 eq per kg of Co in $CoSO_4 \cdot 7H_2O$.

Production of $NiSO_4{\cdot}6H_2O$

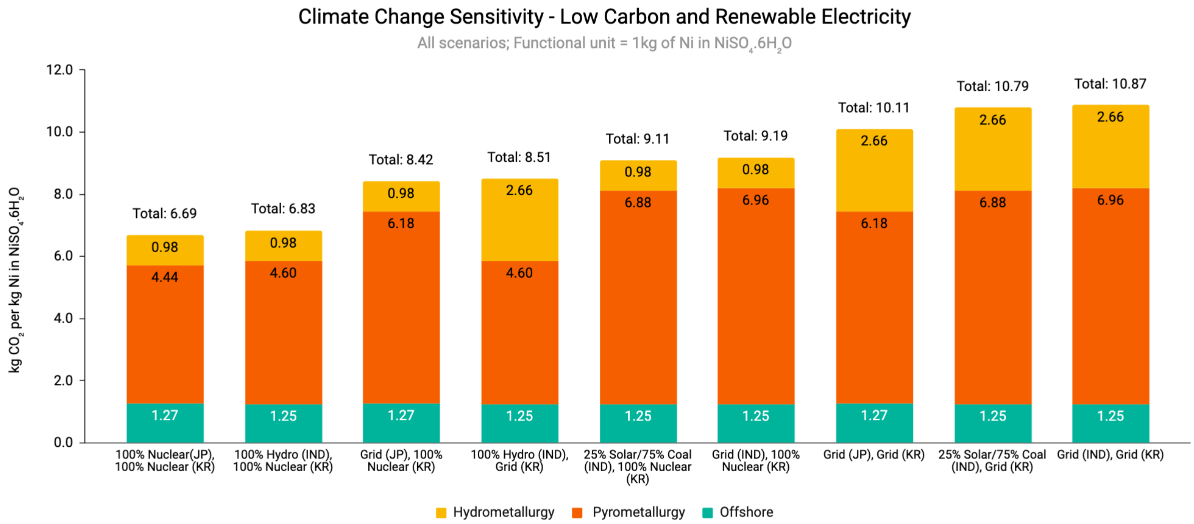

Figure 35: Sensitivity Analysis of the Variation in Global Warming Potential Impacts of $NiSO_4{\cdot}6H_2O$ Production with the Application of Various Low Carbon and Renewable Electricity Mixes.

For $NiSO_4{\cdot}6H_2O$, pyrometallurgy remains the dominant contributor to total climate change impacts. Offshore emissions vary slightly, ranging between 1.25 kg CO_2 eq and 1.27 kg CO_2 eq per kg of Ni in $NiSO_4{\cdot}6H_2O$, depending on whether pyrometallurgy is conducted in Indonesia or Japan.

The best-case scenario, which utilises nuclear energy in both Japan for pyrometallurgy and South Korea for hydrometallurgy, results in total emissions of 6.69 kg CO_2 eq per kg of Ni in $NiSO_4{\cdot}6H_2O$. On the other hand, the worst-case scenario, using grid energy for both pyrometallurgy in Indonesia and hydrometallurgy in South Korea, results in 10.87 kg CO_2 eq per kg of Ni in $NiSO_4{\cdot}6H_2O$.

8.1.2. Sensitivity to the Replacement of Coal with Natural Gas used for Heating

An additional sensitivity analysis was conducted to determine the impact when coal is replaced with natural gas for heating during the pyrometallurgy stage. Those results are shown in **Figure 36** (MnSiO3, matte, and dry nodules processed) and **Figure 37** (copper cathode, $CoSO_4{\cdot}7H_2O$, $NiSO_4{\cdot}6H_2O$). It can be seen that the results of the pyrometallurgy stage (and thus the total results) decrease by approximately 0.11 per kg CO_2eq per kg dry nodules processed and per kg Mn in $MnSiO_3$, 0.09 kg CO_2eq. Per kg matte, 0.16 kg CO_2eq per kg copper cathode, 0.15 kg CO_2eq per kg Co in $CoSO_4{\cdot}7H_2O$ per kg Ni in $NiSO_4{\cdot}6H_2O$.

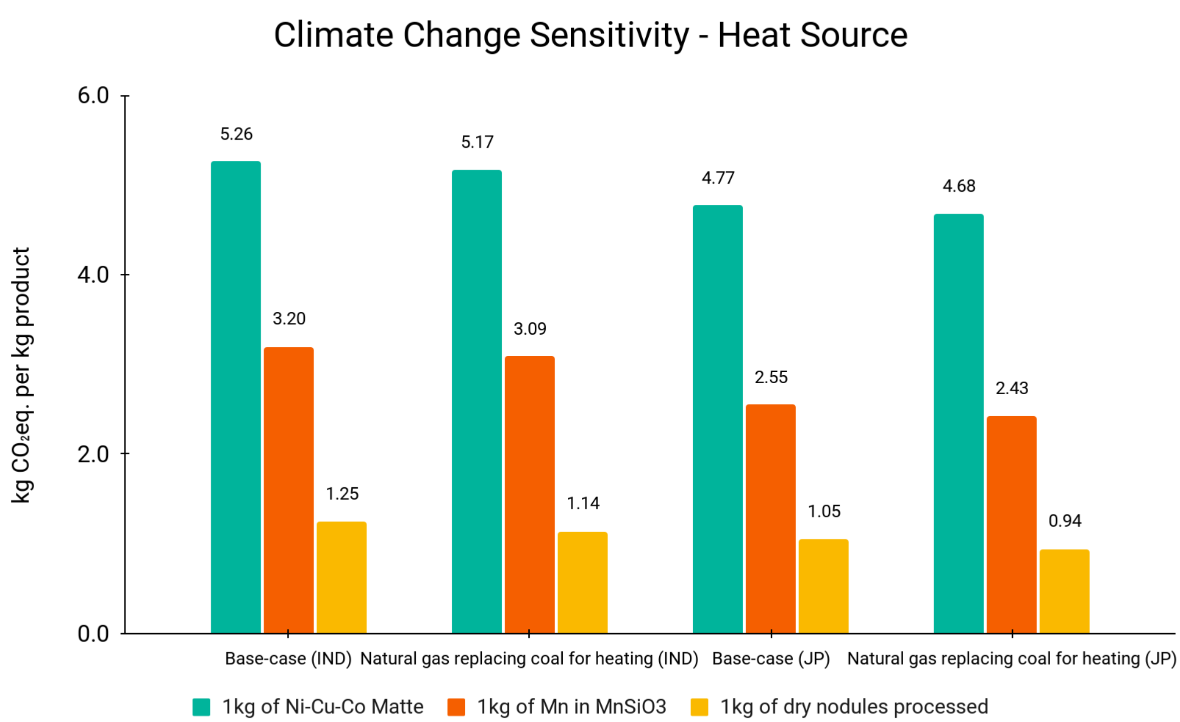

Figure 35: Sensitivity Analysis of the Variation in Global Warming Potential Impacts for the processing of 1kg of dry nodules, the production of NI-Cu-Co matte, and the production of $MnSiO_3$ when natural gas replaces coal for heating in pyrometallurgy.

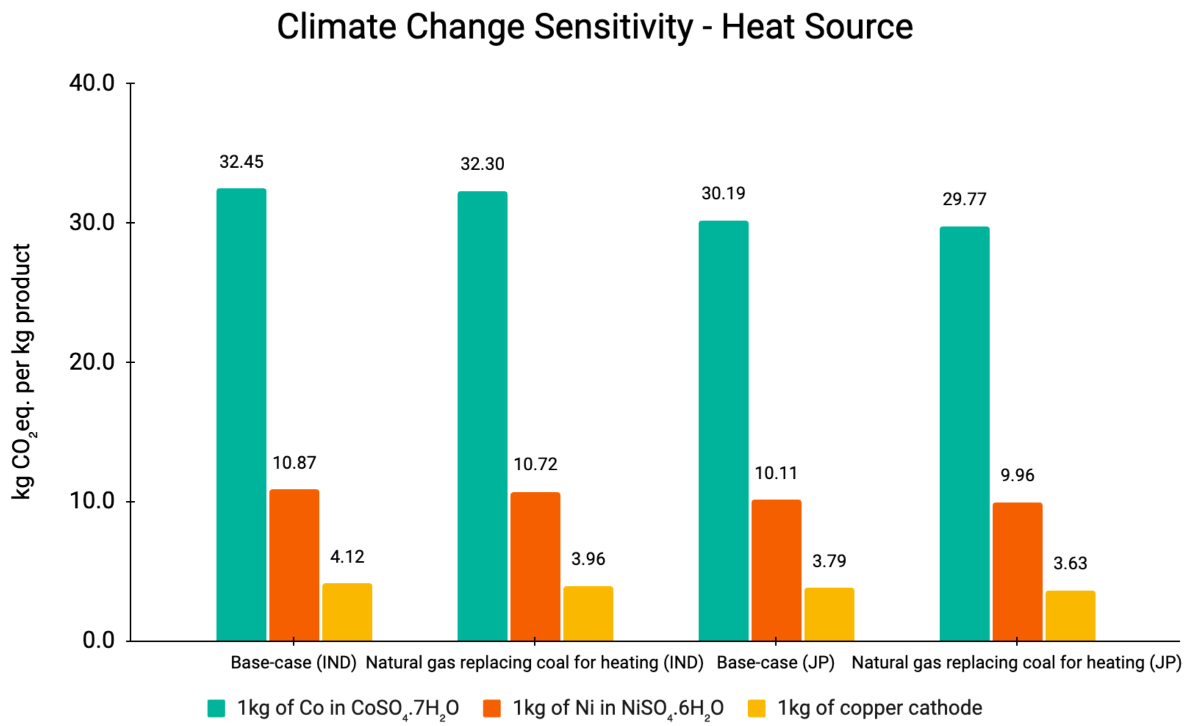

Figure 36: Sensitivity Analysis of the Variation in Global Warming Potential Impacts for the production of 1kg of copper cathode, 1 kg of Ni in NiSO4·6H2O, and 1kg of Co in CoSO4·7H2O when natural gas replaces coal for heating in pyrometallurgy.

8.1.3. Sensitivity to Allocation Methodology Applied

Two further sensitivity analyses were conducted based on allocation. The first analysis was conducted on the economic allocation using 10 year average forecast values for copper, cobalt, and nickel metal from the year 2026-2035 using values provided by the CRU group.[45] This sensitivity is shown in **Figure 37**. The climate change impact for copper cathode is 39% higher than the base case, the climate change impact for Ni (22.4%) in $NiSO_4{\cdot}6H_2O$ is 5.4% lower than the base case and the climate change impact for Co (21.%) in $CoSO_4{\cdot}7H_2O$ is 30.7% lower than the base case when the 10-yr forecast average values are used.

The second sensitivity analysis was conducted using allocation by metal mass. When metal mass based allocation is employed, the climate change impact for copper cathode is 94% higher than the base-case, the climate change impact for Ni (22.4%) in $NiSO_4{\cdot}6H_2O$ is 14% lower than the base-case, and the climate change impact for Co (21.%) in $CoSO_4{\cdot}7H_2O$ is 71% lower than the base-case.

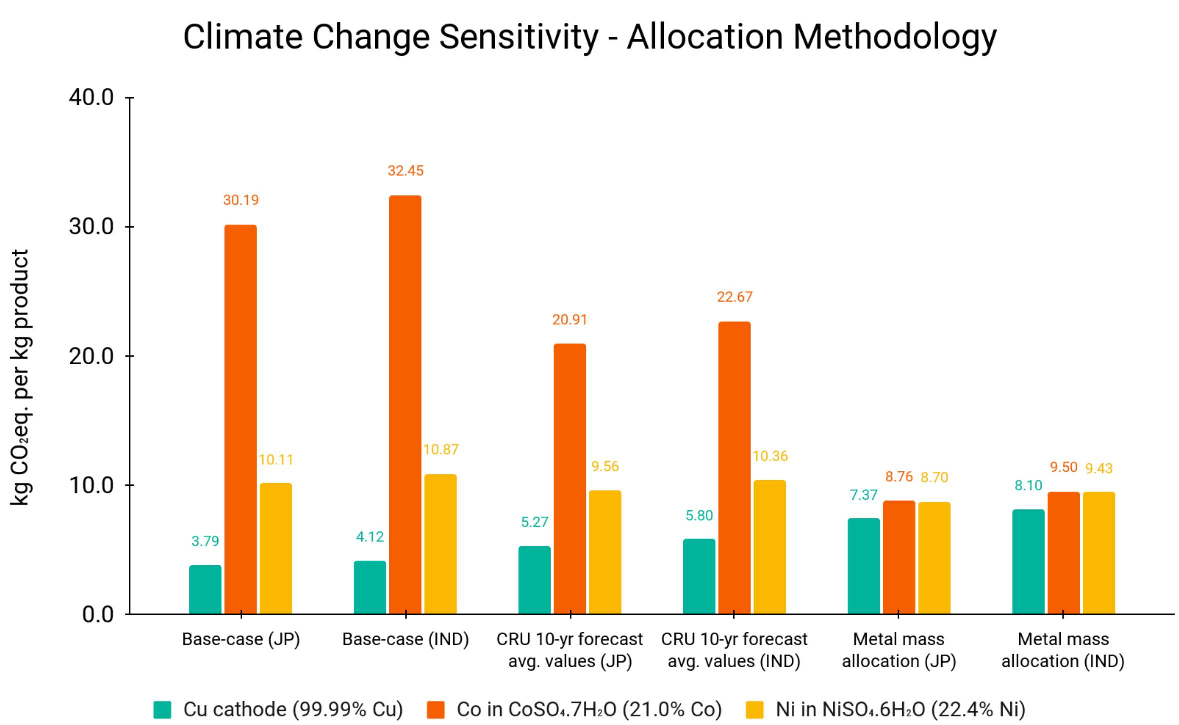

Figure 37: Sensitivity Analysis of Global Warming Potential for TMC's Cu, Ni, and Co Products.

8. Conclusions and Recommendations

8.1. Conclusions

The climate change impact of processing the dry polymetallic nodules, and for producing Ni-Cu-Co matte, $MnSiO_3$, copper cathode, Co in $CoSO_4{\cdot}7H_2O$, and Ni in $NiSO_4{\cdot}6H_2O$ was assessed based on the production location of the matte, comparing Indonesia and Japan.

For processing of the dry polymetallic nodules, when pyrometallurgy occurs in Japan on the national grid the result is 1.05 kg CO_2eq. This result increased to 1.25 kg CO_2 eq when pyrometallurgy occurs in Indonesia on the national grid.

For the production of $MnSiO_3$, when pyrometallurgy occurs in Japan on the national grid the result is 2.55 kg CO_2eq. This result increased to 3.21 kg CO_2 eq when pyrometallurgy occurs in Indonesia on the national grid.

For the production of Ni-Cu-Co matte, when pyrometallurgy occurs in Japan on the national grid the result is 4.77 kg CO_2eq. This result increased to 5.26 kg CO_2 eq when pyrometallurgy occurs in Indonesia on the national grid.

For the production of copper cathode, when the matte is produced in Japan on the national grid the climate impact is 3.79 kg CO_2 eq per kg copper cathode, primarily driven by emissions from pyrometallurgical processes and electricity for operations. This result increased to 4.12 kg CO_2 eq when the production of the matte occurs in Indonesia on the national grid.

The climate change impact for Co in $CoSO_4{\cdot}7H_2O$ was 30.19 kg CO_2eq per kg Co in $CoSO_4{\cdot}7H_2O$ when the Ni-Cu-Co matte was produced in Japan on the national grid. When the production of the matte takes place in Indonesia on the national grid, this impact increased to 32.45 kg CO_2eq.

A similar trend was observed for $NiSO_4{\cdot}6H_2O$ production, where the climate impact when the matte was produced in Japan on the national grid is 10.11 kg CO_2 eq per kg Ni in $NiSO_4{\cdot}6H_2O$, while this impact increased to 10.87 kg CO_2eq per kg Ni in $NiSO_4{\cdot}6H_2O$ when the matte was produced in Indonesia on the national grid.

Sensitivity analysis was conducted to evaluate the impact of various low-carbon and renewable electricity sources that TMC may utilise in the future. Additionally, the analysis considered the potential shift from coal to natural gas for heating, as well as allocation methodology applied.

Climate change impacts were found to be in the range of 0.65 - 1.25 kg CO_2 eq per kg of dry nodules processed, 1.74 - 3.21 kg CO_2 eq per kg Mn in $MnSiO_3$, 3.66 - 5.26 kg CO_2 eq per kg Ni-Cu-Co matte, 2.28 - 8.10 kg CO_2 eq per kg copper cathode, 6.69 - 10.87 kg CO_2eq per kg Ni in $NiSO_4 \cdot 6H_2O$; and 8.76 - 32.45 kg CO_2eq per kg Co in $CoSO_4 \cdot 7H_2O$.

Further results regarding other environmental impact categories are provided in the Appendices.

The primary limitation of this study, applicable to both projects, is the uncertainty associated with conducting an LCA at the pre-feasibility stage. Since the project is in development, some data and process definitions may evolve as it transitions to full-scale operations. To enhance accuracy, updating the LCA once TMC's facilities are fully operational is recommended, allowing for refined assumptions.

Additionally, this study does not assess the environmental impacts related to polymetallic nodule collection from the seafloor, as these lie outside the scope of the current analysis. Therefore, the results presented should be considered in light of these limitations.

We have greatly enjoyed collaborating with TMC on this project and look forward to continuing our relationship in the pursuit of minimising the environmental impacts of manufacturing critical products.

8.2. Recommendations

Minviro has several recommendations for TMC to improve the quality of this LCA and to improve the environmental performance of the various production routes evaluated in this report.

- There are inherent uncertainties associated with conducting an LCA on a project in the pre-feasibility phase. As the project progresses toward feasibility study and commercial scale operations, some data and process definitions may change. Therefore, it is vital to revisit and refine the LCA to account for these developments, ultimately improving the assessment's accuracy.
- Once the project is operational, it is recommended to reproduce the LCA annually using actual production data. This will provide TMC with a clear understanding of the CO_2 equivalent emissions occurring each year, facilitating better emissions tracking and management. As the project develops, it is crucial to revise the LCA to incorporate

updated engineering data. This should occur once the project reaches a higher level of definition, such as during the definitive feasibility study. Ensuring the LCA reflects the most current data will enhance the accuracy and relevance of the findings.

- While this study did not assess the environmental impacts related to polymetallic nodule collection from the seafloor, future analyses should consider this aspect. Conducting additional assessments in conjunction with standard LCA methodologies will provide a more comprehensive understanding of the environmental implications of the entire project lifecycle.
- Transport of reagents to the pyrometallurgy and hydrometallurgy facilities has been excluded due to the lack of data. Future LCA work should include a complete data set for the transport of reagents to the site.
- The infrastructure and equipment used in this project have not been taken into account in this LCA. On average, over a LOM of 10 years, 0.05-0.5 kg CO_2 eq. per kg of product is consumed for the production and utilisation of the equipment. For future LCAs, this should be taken into account.

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10. Appendix A – Description of Impact Categories (excluding Climate Change)

10.1. Acidification Potential

Acidification potential refers to the acidifying impact on the environment (soil, groundwater, surface water) caused by acidic gases such as sulphur dioxide (SO_2), nitrous oxides (NO_x), and reduced nitrogen (NH_x).[16,17] These acidic gases react with water in the atmosphere to form "acid rain", a process known as acid deposition. When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem damage to varying degrees depending upon the nature of the ecosystems. The cause-and effect relationship from acidifying emissions to change in soil composition and damage to the environment can be found in **Figure B1**.

Acidification potential is expressed using the reference unit, **mol H^+ equivalent**. The model does not take account of regional differences in terms of which areas are more or less susceptible to acidification. It accounts only for acidification caused by SO_x and NO_x. In the Environmental Footprint Methodology, acidification potential is determined by quantifying accumulated exceedance (AE) of acidifying substances (e.g., SO_2 and NO_x) in terrestrial and aquatic environments.[17,18] The release of hydrogen atoms (H^+) from both sulfur- and nitrogen-containing compounds can lead to acidification when it exceeds the critical load of the aquatic or terrestrial ecosystem.

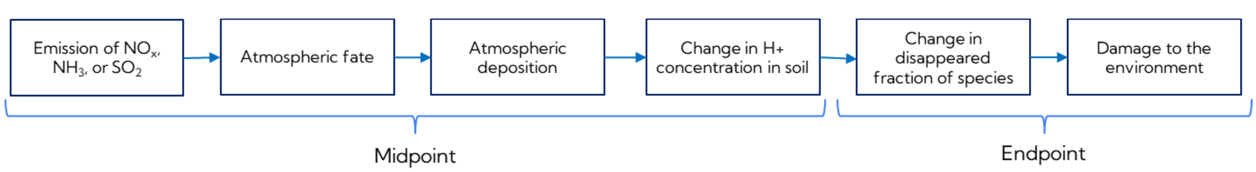


Figure B1. Cause-and-effect chain from acidifying emission to change in soil composition (midpoint indicator) and damage to the environment (endpoint indicator)

10.2. Particulate Matter

PM model recommended by UNEP[19]

Fine particulate matter (PM2.5) is considered to be one of the most important environmental factors contributing to the global human disease burden.[19] The particulate matter impact category quantifies human health effects associated with exposure to PM2.5. The impact is calculated by calculating the direct emissions of PM2.5 along with data on emission location such as population density and height of PM2.5 release. This data will inform the **disease incidences** emitted. The same approach is calculated for background PM2.5 emissions. The characterization factors provided by the model for the average Emissions Reduction Fund (ERF) were collected as they are published by model developers and then mapped to the ILCD elementary flow list. The PM2.5 and PM10 characterization factors are from the reference elementary flow of the ILCD.[8]

10.3. Eutrophication Potential

Eutrophication is described as a cascade of processes that occur in aquatic and terrestrial ecosystems in response to an increase in nutrient inputs.[20] In aquatic environments (freshwater and marine), the enrichment of nutrients causes accelerated growth of algae and higher-form plants to produce undesirable disturbance to the ecosystem in the water. In aquatic environments, excessive plant growth like algae in rivers causes severe reductions in water quality and animal populations.[21] In terrestrial environments, excessive atmospheric load of nutrients results in excessive nutrients to soil, changing the soil composition and diversity.[20,22] The cause-and-effect chain for nitrogen and phosphorus emissions can be found in **Figure B2** below.

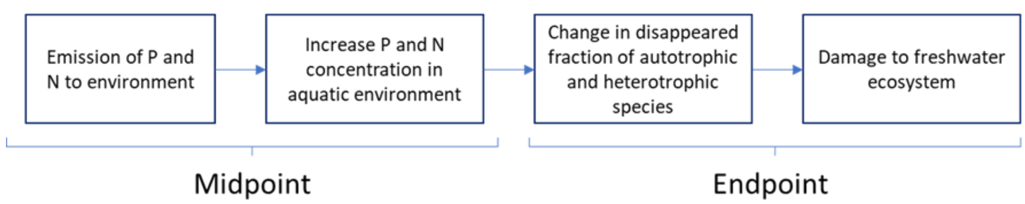


Figure B2. Cause-and-effect chain for nitrogen and phosphorus emissions in aquatic environments, as an example.

Eutrophication potential is measured by modelling the fate and flows of Phosphate (P) and Nitrogen (N) emissions into the environment, such as ammonia, nitrates, nitrogen oxides, and phosphate ions (PO_4^{3-}). The method includes the direct and indirect impacts of eutrophication drivers such as fertilisers, manures, and other organic by-products. In the Environmental

Footprint Methodology, the potential impact of eutrophication is divided into three subcategories.

Freshwater Eutrophication

With respect to freshwater eutrophication, phosphorus (P) is the limiting factor, therefore only P-compounds are considered for the assessment of freshwater eutrophication. The reference unit is expressed as **kg P equivalent**. This category is based on the work of Stuijs.[23]

Marine Eutrophication

With respect to marine eutrophication, nitrogen (N) is the limiting factor, therefore only N-compounds are considered in the assessment of marine eutrophication. The reference unit is expressed as **kg N equivalent**. This category is based on the work of Stuijs.[23]

Terrestrial Eutrophication

With respect to terrestrial eutrophication, the concentration of nitrogen (N) is the limiting factor. Units of the characterization factor are **mol N equivalent**. This category is based on the work of Seppälä and Posch.[16,17]

10.4. Freshwater Ecotoxicity

Comparative toxic unit for ecosystems (CTUe) [24]

Chemical substances released into the environment are distributed across the various environmental compartments such as air, water, and soil. The potential of a chemical substance to cause harm (damage) to ecosystems (i.e., ecotoxicity potential) depends on its intrinsic properties (e.g., potency to induce an ecotoxicological effect), the characteristics of organisms, and the amount of time- and space- integrated exposure (which determines the effective exposure concentration) of the organisms in that compartment to the specific chemical.[24]

Ecotoxicity potential is divided into three subcategories: freshwater, marine and terrestrial and is expressed with Comparative Toxic Unit for ecotoxicity (CTUe). With respect to freshwater ecotoxicity, this is represented by the toxic effect on aquatic freshwater species in the water column. The impact on other ecosystems, such as sediments, are not reflected in current general practice. The freshwater ecotoxicity impact is based on the USEtox model.[24] All USEtox™ factors were implemented in accordance to the correspondence in the emission compartments (air, water, soil). Freshwater ecotoxicity is expressed as **CTU equivalent**.

10.5. Ionising Radiation: Human Health

According to the United Nations Environmental Program (UNEP)[25] and The UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[26], Ionising radiation, emitted from unstable atomic nuclei, can interact with other atoms to create ions. Exposure can occur from various sources and result in deterministic effects, such as acute radiation syndrome and hair loss, or stochastic effects, like cancer and inheritable diseases (**Figure B3**). The intensity of deterministic effects increases with higher doses, while the occurrence rate of stochastic effects rises with higher doses, but their severity remains constant.

The Environmental Footprint (EF) category of Ionising Radiation is a midpoint indicator which accounts for the adverse human health effects caused by radioactive releases. It measures the impact of different ionising radiations on human health, comparing them to **kilobequerels of Uranium 235** (kg U235 eq).[27-30] In the EF methodology, ionising radiation is based on the Fate-exposure model by Frischknecht 2000[31], which assesses site-specific models for French nuclear facilities but can also be applied more broadly. In the fate analysis of the Frischknecht 2000 model, data from sites like mines and power plants, as well as surrounding conditions like population and weather, are based on French and European conditions. The models used in this analysis consider 100,000 years to account for the longevity of some radionuclides. Different models are employed for different types of emissions, such as atmospheric discharges and liquid releases into rivers and seas. For globally dispersed radionuclides, simplified models are used. It's important to note that confidence in the results of globally dispersed radionuclides is generally low due to the simplicity of the models and the small doses spread over a large population for a long time.

Exposure analysis looks into how human exposure to radiation increases in the air, water, soil, and vegetation due to the transport, dispersion, and deposition of radionuclides. The pathways for this exposure include atmospheric and liquid discharges, with the aquatic pathway further divided into river and marine releases. Increased radiation in air and soil leads to additional external radiation. Humans are exposed through direct inhalation, external irradiation from air and soil, and ingestion of plants and animals, leading to additional collective doses. The main exposure pathways for radionuclides relevant to electricity supply systems are diet intake for C-14 and I-129, external irradiation for Kr-85, and inhalation for Rn-222.

However, The model does not consider health effects from large accidental releases, occupational exposure, or radioactive waste disposal, and it does not cover effects on ecosystems. Therefore, it primarily reflects stochastic health effects related to cancer. Another limitation is low data availability and lack of accounting for ionising radiation arising from the disposal of nuclear waste.[32] Ionising radiation lacks the reflection of naturally occurring radioactive material (NORM)[33] in ore deposits. Still, it would reflect the ionising radiation impact in relation to the electricity mix used in ore mining. **Therefore, This EF category is particularly relevant when comparing different energy-generation systems because the share of nuclear power in market mixes impacts this category**.[34]

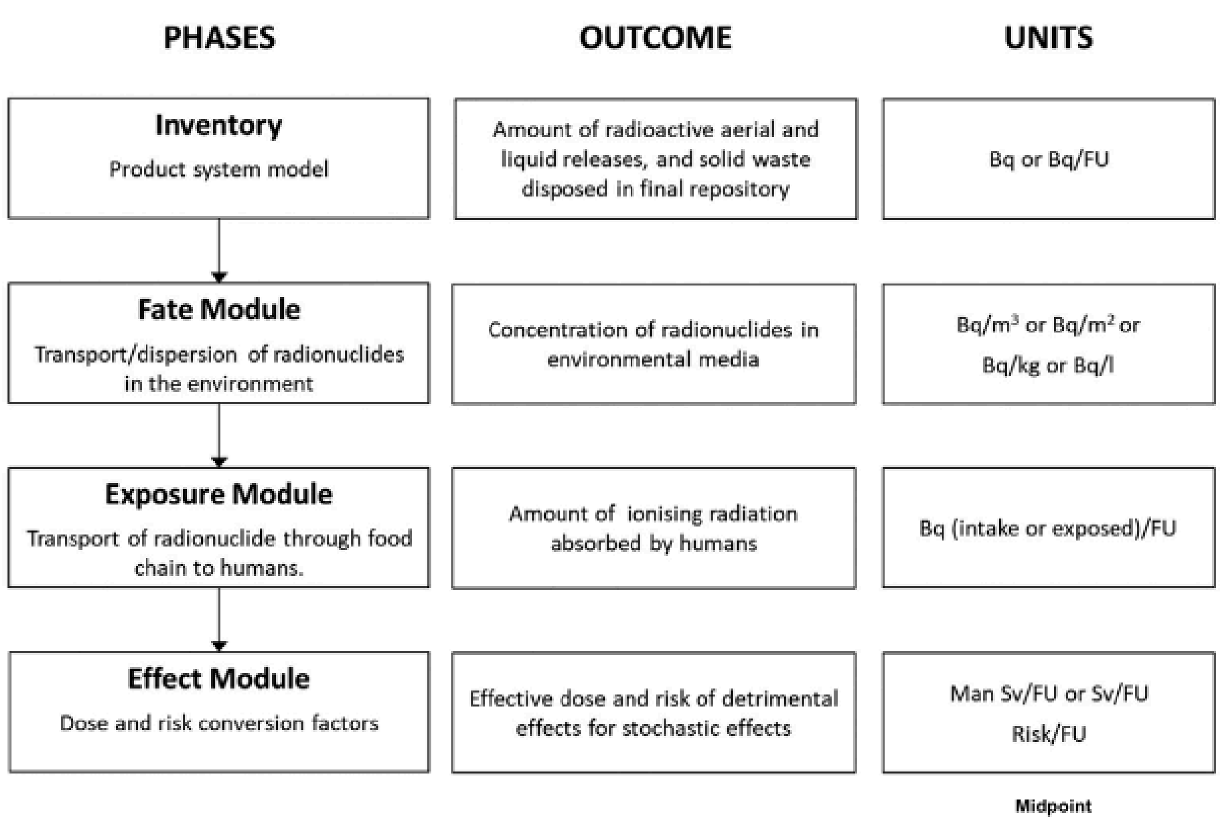


Figure B3. Impact pathway stages for ionising radiation up to Midpoint by Paulilo et al.[32]

10.6. Photochemical Oxidant Formation: Human Health

Photochemical ozone formation is an environmental impact category in LCA, often associated with terms like ozone formation, photochemical ozone creation, photo smog, or summer smog under different LCIA methodologies.[35] The naming and specifics may slightly differ based on the included substances and assumed atmospheric conditions in the models, however, they all refer to the formation of ground-level ozone through a complex series of chemical reactions, involving nitrogen oxides (NOx) and volatile organic compounds (VOCs). It occurs via photochemical oxidation of VOCs and carbon monoxide with NOx and sunlight. It's hazardous when trapped at ground level of the atmosphere (troposphere) under certain weather conditions, as ground-level ozone is a harmful air pollutant and a major component of smog.

In LCA, the EF midpoint impact category of these substances is quantified in terms of Non-Methane Volatile Organic Compounds (NMVOC) equivalents.[36-39] The cause-and-effect chain of photochemical ozone formation to damage to human health and ecosystems is presented in **Figure B4**. The LOTOS-EUROS model, applied in ReCiPe 2008, is one of the methods used to study this phenomenon and it's recommended as the methodology of choice by the EF impact assessment method.[36,38] The model has undergone peer review and comparison with other models and offers factors for both NOx and NMVOCs, and it is particularly relevant to the European setting. The model is strongly connected to the recommended midpoint and is flexible for use in other continents and globally, provided the necessary effect data is incorporated.[36,39] There are connections existing between the effects of photochemical oxidant creation on ecosystem diversity and human health. It attacks organic compounds in both animals and plants and escalates the incidence of breathing issues when cities experience photochemical smog, also known as "summer smog".[36]

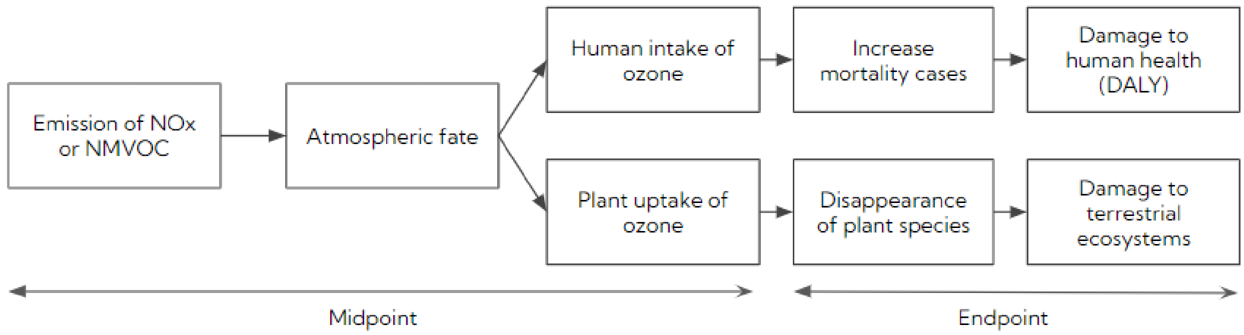


Figure B4. Cause-and-effect chain for photochemical oxidant formation and the damage to human health and ecosystems.

10.7. Human toxicity: carcinogenic and non-carcinogenic

Comparative Toxic Unit for Humans (CTUh).

Chemical substances released into the environment are distributed across the various environmental compartments such as air, water, and soil. The potential of a chemical substance to cause harm (damage) to human health (i.e., human toxicity potential) by being ingested or absorbed depends on the chemical's environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect).

Human toxicity potential is divided into two subcategories: human toxicity (carcinogenic) and human toxicity (non-carcinogenic) and is expressed in units of **Comparative Toxic Unit for Humans (CTUh)**. Human toxicity (carcinogenic) refers to the potential for causing cancer, whereas human toxicity (non-carcinogenic) refers to potential of chemical substances to cause non-cancerous ill-health impacts. Like for freshwater ecotoxicity, human toxicity (carcinogenic) and human toxicity (non-carcinogenic), the potential impact is based on the USEtox model. The cause-and-effect chain of human toxicity (carcinogenic and non-carcinogenic) is presented in **Figure B5**.

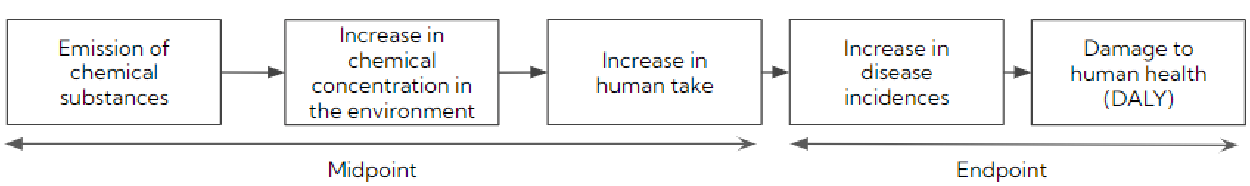


Figure B5. Cause-and-effect chain human toxicity from emission of chemical substances and damage to human health.

10.8. Ozone depletion

The ozone depletion potential (ODP) serves as a measure of the degradation of stratospheric ozone caused by emissions of ozone-depleting substances (ODS) (**Figure B6**), including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and other halocarbons.[38] These human-made compounds, emitted primarily through industrial activities, undergo chemical reactions catalysed by UV radiation in the stratosphere, resulting in the breakdown of ozone molecules and a subsequent reduction in ozone concentration.[40]

The calculation of ODP by the World Meteorological Organisation (WMO) relies on observational data to assess the fraction release of chlorine (Cl) and bromine (Br) from ODS.[40] To facilitate comparison across different ODS, the ozone depletion potential is weighted against the reference value of CFC-11, providing a relative measure of a substance's ability to deplete ozone, with CFC-11 assigned a value of 1.[41] This approach enables the evaluation of the potential impact of various ODS on the Earth's ozone layer, aiming to achieve an equilibrium state of total ozone reduction.

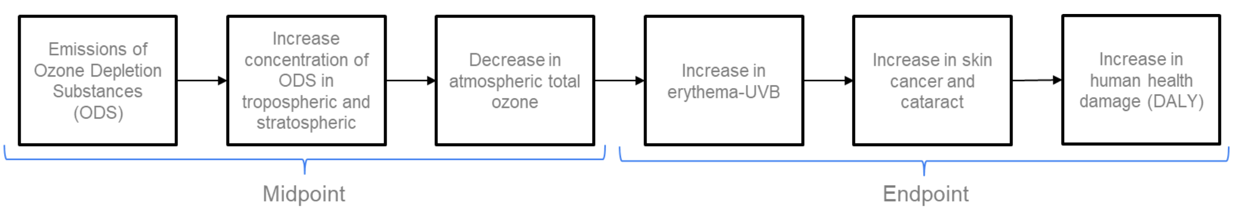


Figure B6. The cause-and-effect chain for emissions of ozone-depleting substances (ODS) results in a potential ozone depletion layer (at midpoint level) and damage to human health (at endpoint level).

10.9. Resource depletion: metals and minerals

"Mineral resources" are non-renewable chemical elements including metals (e.g., copper), minerals (e.g., gypsum), and aggregates (e.g., sand) as embedded in a natural or anthropogenic stock, that can hold value for humans to be made use of in the technosphere. Environmental impacts related to their use and/or consumption can be achieved via a multitude of ways, including measuring depletion from a defined reserve.

Within the EF3.1 methodology, Abiotic Resource Depletion Potential (ADP) quantifies the use of non-renewable resources throughout the life cycle of a product or process, implying the extent to which finite resources are consumed or diminished.[28-30] The calculation considers the types and quantities of metals and minerals involved in the production, use, and disposal phases of the product or process under evaluation, plus the environmental burdens associated with extracting and processing these ingredients. The cause-and-effect chain of resource depletion - metals and minerals is presented in **Figure B7**.

The characterization factor for ADP is derived from two values: "ultimate reserves" and "extraction rate". The term “ultimate reserve” encompasses both the concentrated ores and mineral deposits, but also the scattered occurrences in the earth’s crust, implying the total availability of the specific element in the environment. The “extraction rate” of a given material is collected from the United States Geological Survey (USGS). Both reserve and extraction data for forming baselines are under constant scrutiny for updating.[42]

The ADP (minerals and metals) calculation is normalised to kilograms (kg) of “antimony equivalent” (Sb eq.).[28-30,42] This is similar to CO2 eq. being used to represent all greenhouse gases. The choice of the antimony equivalent as a unit is part of an attempt to express the environmental impacts of resource consumption in a standardised and comparable way. Antimony is often chosen as a reference material because it is relatively scarce, lies in the middle of the periodic table, is used in various industrial applications and has documented environmental implications associated with its extraction and use, and thus serves as a reasonable proxy for all other materials. The process enables the integration of diverse resource types into a comprehensive assessment, allowing for a more holistic understanding of the environmental implications associated with resource use.

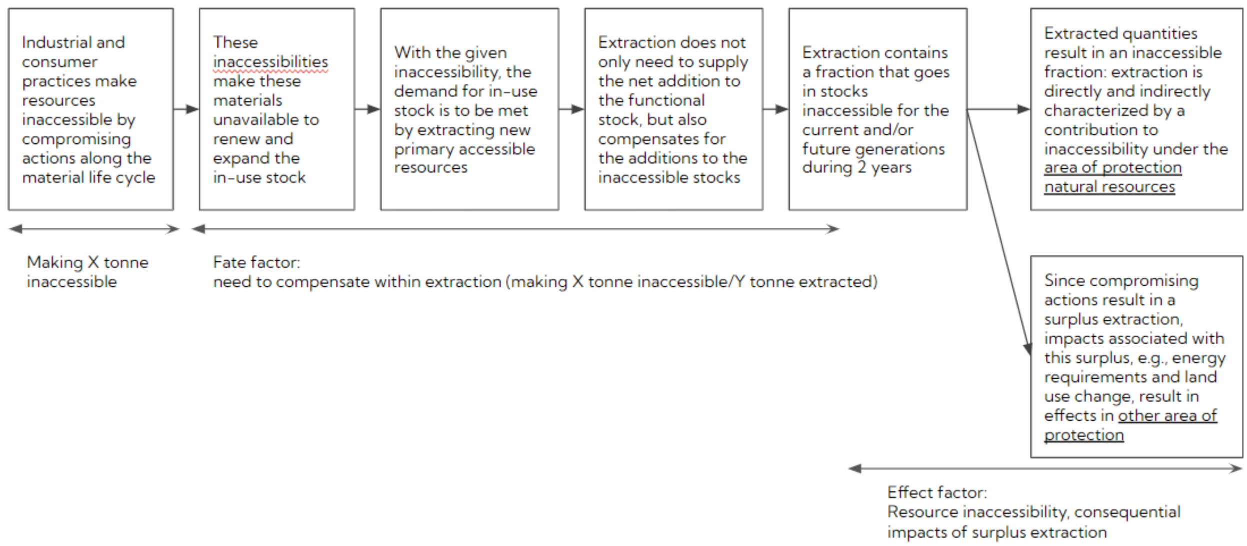


Figure B7. The cause-and-effect chain for resource depletion - metals and minerals.

10.10. Resource depletion: Fossil fuels

"Fossil fuels" are non-renewable natural energy resources formed from the remains of ancient organisms, primarily plants and microscopic organisms, which include coal, petroleum and natural gas. Environmental impacts related to their use and/or consumption can be achieved via a multitude of ways, including measuring depletion from a defined reserve of energy.

Within the EF3.1 methodology, Abiotic Resource Depletion Potential (ADP) quantifies the use of non-renewable resources throughout the life cycle of a product or process, implying the extent to which finite resources are consumed or diminished.[28-30] This assessment identifies the types and quantities of fossil fuels consumed throughout the life cycle of the product or process under scrutiny. This encompasses extraction, transportation, refining, and eventual combustion or usage phases of the energy required to make the product being assessed. This will include electricity generation and fuelling of machinery for mining, processing and manufacturing.

Similar to Resource Depletion: metals and minerals, the characterization factor for ADP is derived from two values: "ultimate reserves" and "extraction rate". The term "ultimate reserve" encompasses measured fossil fuel deposits in the earth's crust, implying the total availability of usable energy in the environment. The “extraction rate” of a given material is collected from the United States Geological Survey (USGS). Both reserve and extraction data for forming baselines are under constant scrutiny for updating.[42]

One fundamental aspect of the methodology involves normalising the impacts of various fossil fuels into a single indicator to enable meaningful comparisons. In many cases, this normalisation is achieved by expressing impacts in megajoule (MJ) equivalents.[28-30] The rationale behind this is to provide a common unit for comparing the energy content and environmental burdens associated with different fossil fuels, allowing effective communication of the severity of fossil fuel depletion impacts in terms of energy scarcity and environmental consequences. This holistic approach enables stakeholders and decision-makers to identify critical hotspots in the supply chain where interventions can be targeted to mitigate resource depletion impacts. A similar cause-and-effect relationship for metals and minerals could also be applied to fossil fuel depletion.

11. Appendix B – Results For All EF Impact Categories

Environmental impacts associated with the collection and processing of 1kg of dry polymetallic nodules, and the production of 1kg of Mn in $MnSiO_3$, Ni-Cu-Co matte, copper cathode, Co in $CoSO_4 \cdot 7H_2O$, and Ni in $NiSO_4 \cdot 6H_2O$ for the base-case scenarios. The impacts are broken down by offshore operations, TMC's pyrometallurgy process (i.e., the production of $MnSiO_3$), and the hydrometallurgy process. The results are first shown in tabular form, followed by graphical representations.

Table: C1. Environmental Impacts per kg of Dry Nodules processed – Pyrometallurgy in Indonesia

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	2.58E-01	9.63E-01	2.91E-02	1.25E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	3.45E-03	6.44E-03	-3.29E-05	9.86E-03
Freshwater Eutrophication	kg P-Eq	2.34E-06	1.11E-03	9.88E-06	1.13E-03
Terrestrial Eutrophication	mol N-Eq	1.89E-03	1.10E-02	-3.11E-04	1.26E-02
Freshwater Ecotoxicity	CTU	2.40E-01	2.66E+00	-5.81E+00	-2.91E+00
Marine Eutrophication	kg N-Eq	1.73E-04	1.23E-03	-7.52E-05	1.33E-03
Ionising Radiation	kg U235-Eq	5.86E-04	1.80E-03	1.02E-02	1.26E-02
Photochemical Ozone	kg NMVOC	9.95E-04	3.06E-03	-1.33E-07	4.05E-03
Carcinogenic	CTUh	2.36E-10	5.91E-10	-2.70E-10	5.58E-10
Non-Carcinogenic	CTUh	1.86E-09	7.36E-09	-4.88E-10	8.73E-09
Respiratory	disease i.	4.46E-08	5.97E-08	-2.22E-10	1.04E-07
Ozone Depletion	kg CFC-11	3.26E-09	2.71E-09	3.94E-10	6.37E-09
Minerals + Metals	kg Sb-Eq	2.80E-08	1.74E-07	-5.77E-06	-5.57E-06
Fossils	MJ	3.22E+00	9.49E+00	5.47E-01	1.33E+01
Water	m3 world eq	3.10E-03	9.87E-02	1.11E-02	1.13E-01
Land	points	1.12E-05	1.45E-03	2.24E-01	2.26E-01

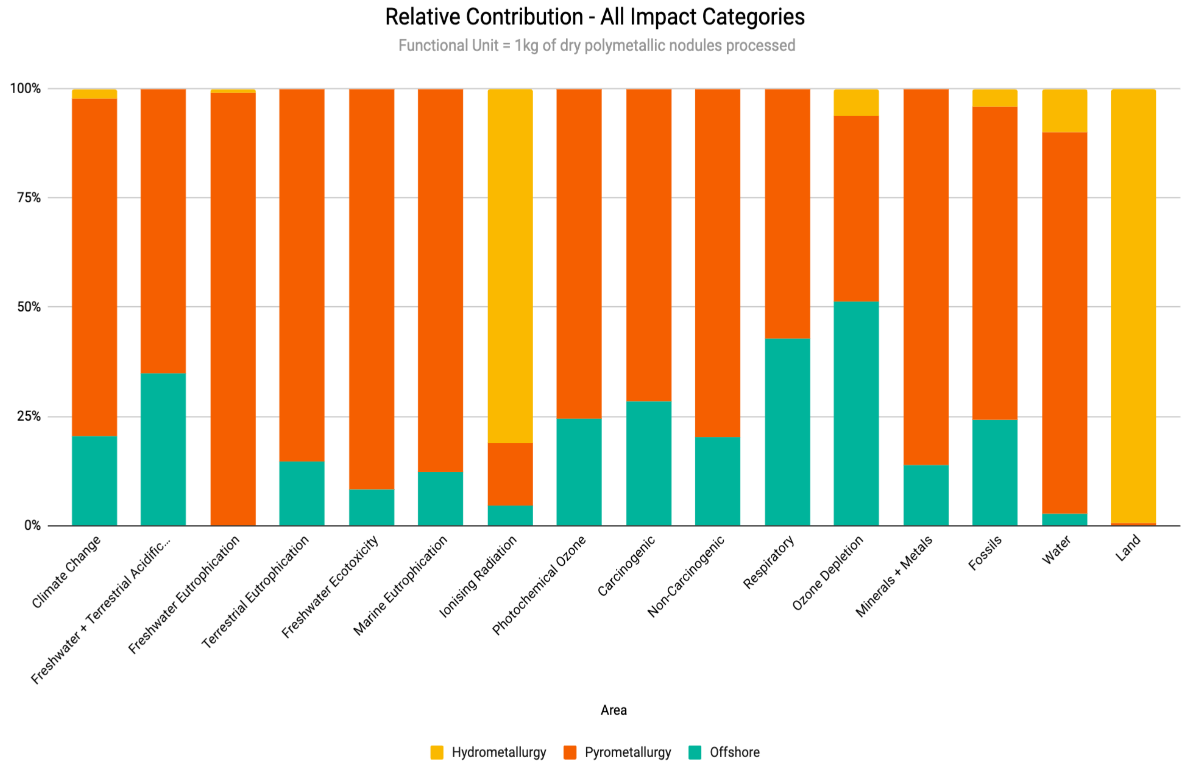


Figure C1: Relative Contribution of all impact categories evaluated in this study per kg of dry nodules collected and processed; Indonesia.

Table C2. Environmental Impacts per kg of Dry Nodules processed – Pyrometallurgy in Japan

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	2.61E-01	7.65E-01	2.91E-02	1.05E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	3.49E-03	7.78E-03	-3.29E-05	1.12E-02
Freshwater Eutrophication	kg P-Eq	2.37E-06	2.70E-03	9.88E-06	2.72E-03
Terrestrial Eutrophication	mol N-Eq	1.91E-03	1.03E-02	-3.11E-04	1.19E-02
Freshwater Ecotoxicity	CTU	2.43E-01	1.55E+00	-5.81E+00	-4.02E+00
Marine Eutrophication	kg N-Eq	1.75E-04	3.23E-03	-7.52E-05	3.33E-03
Ionising Radiation	kg U235-Eq	5.93E-04	2.61E-02	1.02E-02	3.70E-02
Photochemical Ozone	kg NMVOC	1.01E-03	4.75E-03	-1.33E-07	5.75E-03
Carcinogenic	CTUh	2.39E-10	2.48E-03	-2.70E-10	2.48E-03
Non-Carcinogenic	CTUh	1.88E-09	2.48E-03	-4.88E-10	2.48E-03
Respiratory	disease i.	4.51E-08	2.48E-03	-2.22E-10	2.48E-03
Ozone Depletion	kg CFC-11	3.30E-09	2.48E-03	3.94E-10	2.48E-03
Minerals + Metals	kg Sb-Eq	2.83E-08	2.48E-03	-5.77E-06	2.47E-03
Fossils	MJ	3.26E+00	8.13E+00	5.47E-01	1.19E+01
Water	m3 world eq	3.13E-03	5.42E-02	1.11E-02	6.84E-02
Land	points	1.13E-05	2.55E-03	2.24E-01	2.27E-01

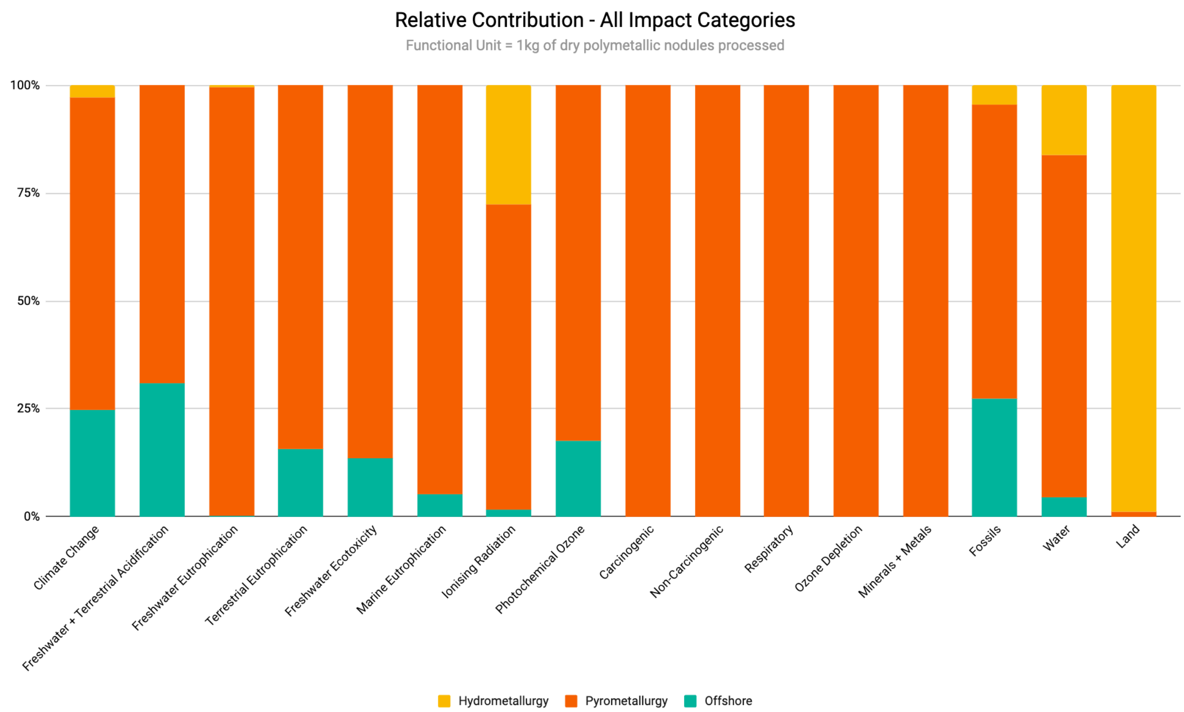


Figure C2: Relative Contribution of all impact categories evaluated in this study per kg of dry nodules collected and processed; Japan.

Table C3. Environmental Impacts per kg Mn in MnSiO3 – Pyrometallurgy in Indonesia

Impact Category	Units	Offshore	Pyrometallurgy	Total
Climate Change	kg CO2-Eq	7.61E-01	2.45E+00	3.21E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	1.02E-02	1.55E-02	2.57E-02
Freshwater Eutrophication	kg P-Eq	6.91E-06	3.12E-03	3.13E-03
Terrestrial Eutrophication	mol N-Eq	5.56E-03	2.81E-02	3.36E-02
Freshwater Ecotoxicity	CTU	7.08E-01	6.94E+00	7.65E+00
Marine Eutrophication	kg N-Eq	5.12E-04	3.18E-03	3.69E-03
Ionising Radiation	kg U235-Eq	1.73E-03	4.94E-03	6.67E-03
Photochemical Ozone	kg NMVOC	2.94E-03	7.77E-03	1.07E-02
Carcinogenic	CTUh	6.98E-10	1.44E-09	2.14E-09
Non-Carcinogenic	CTUh	5.48E-09	1.96E-08	2.51E-08
Respiratory	disease i.	1.31E-07	1.57E-07	2.89E-07
Ozone Depletion	kg CFC-11	9.63E-09	7.65E-09	1.73E-08
Minerals + Metals	kg Sb-Eq	8.27E-08	4.73E-07	5.55E-07
Fossils	MJ	9.51E+00	2.44E+01	3.39E+01
Water	m3 world eq	9.14E-03	2.79E-01	2.88E-01
Land	points	3.29E-05	4.22E-03	4.25E-03

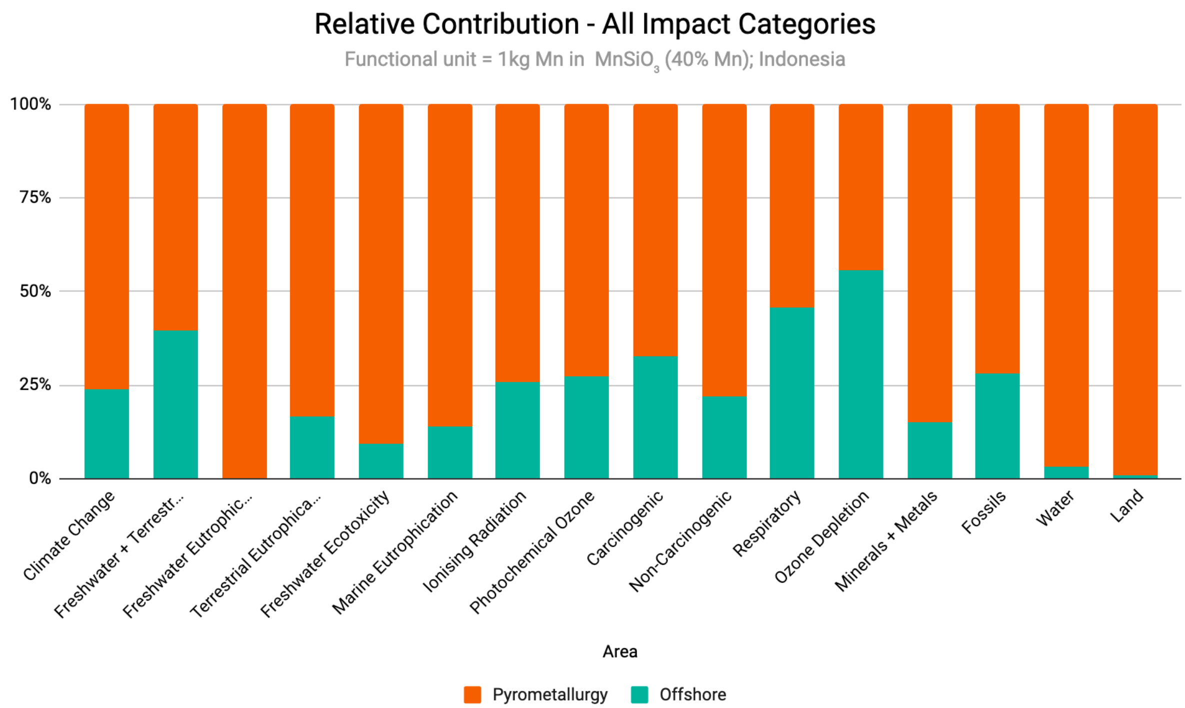


Figure C3: Relative Contribution of all impact categories evaluated in this study per kg of Mn in $MnSiO_3$; Indonesia

Table C4. Environmental Impacts per kg Mn in $MnSiO_3$ – Pyrometallurgy in Japan

Impact Category	Units	Offshore	Pyrometallurgy	Total
Climate Change	kg CO2-Eq	7.70E-01	1.78E+00	2.55E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	1.03E-02	1.18E-02	2.21E-02
Freshwater Eutrophication	kg P-Eq	6.99E-06	5.14E-04	5.21E-04
Terrestrial Eutrophication	mol N-Eq	5.63E-03	1.81E-02	2.38E-02
Freshwater Ecotoxicity	CTU	7.16E-01	3.56E+00	4.28E+00
Marine Eutrophication	kg N-Eq	5.17E-04	1.73E-03	2.24E-03
Ionising Radiation	kg U235-Eq	1.75E-03	6.27E-02	6.45E-02
Photochemical Ozone	kg NMVOC	2.97E-03	5.27E-03	8.24E-03
Carcinogenic	CTUh	7.06E-10	2.02E-09	2.73E-09
Non-Carcinogenic	CTUh	5.54E-09	8.58E-09	1.41E-08
Respiratory	disease i.	1.33E-07	5.12E-08	1.84E-07
Ozone Depletion	kg CFC-11	9.74E-09	1.58E-08	2.55E-08
Minerals + Metals	kg Sb-Eq	8.37E-08	5.82E-07	6.66E-07
Fossils	MJ	9.62E+00	1.94E+01	2.90E+01
Water	m3 world eq	9.24E-03	1.33E-01	1.42E-01
Land	points	3.33E-05	1.68E-04	2.02E-04

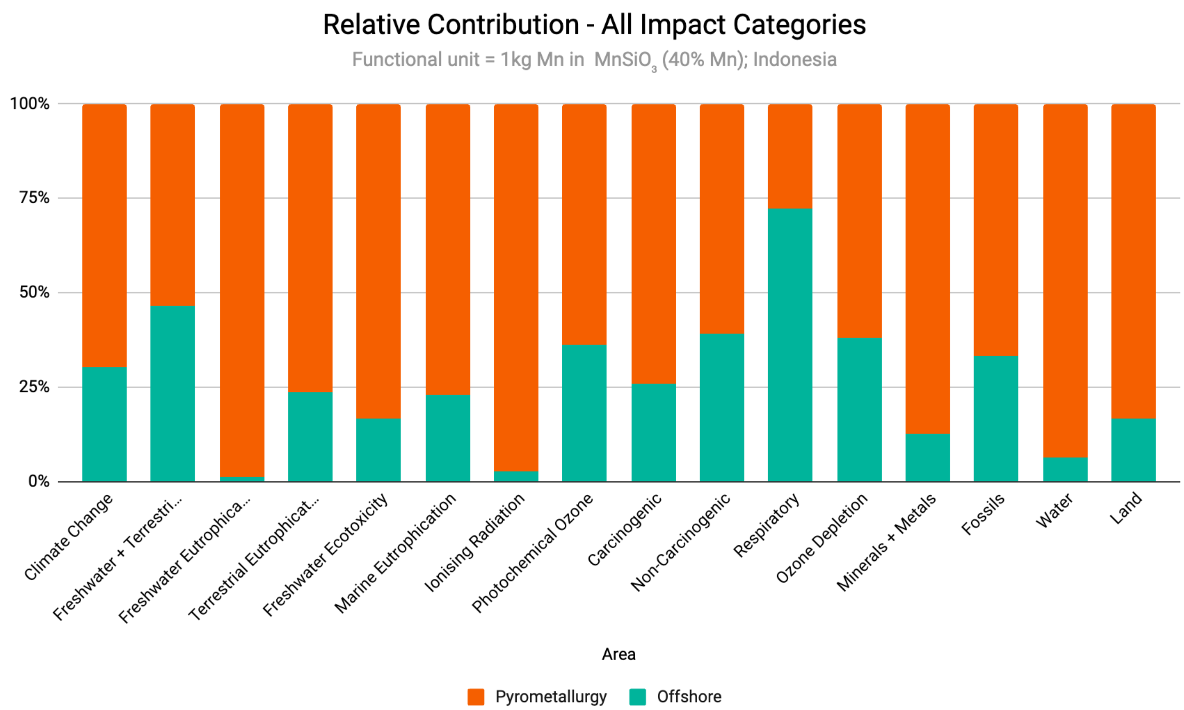


Figure C4: Relative Contribution of all impact categories evaluated in this study per kg of Mn in $MnSiO_3$; Japan

Table C5. Environmental Impacts per kg Matte – Pyrometallurgy in Indonesia

Impact Category	Units	Offshore	Pyrometallurgy	Total
Climate Change	kg CO2-Eq	7.61E-01	4.50E+00	5.26E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	1.02E-02	3.51E-02	4.52E-02
Freshwater Eutrophication	kg P-Eq	6.91E-06	4.07E-03	4.08E-03
Terrestrial Eutrophication	mol N-Eq	5.56E-03	5.26E-02	5.82E-02
Freshwater Ecotoxicity	CTU	7.08E-01	1.21E+01	1.28E+01
Marine Eutrophication	kg N-Eq	5.12E-04	5.58E-03	6.09E-03
Ionising Radiation	kg U235-Eq	1.73E-03	9.19E-03	1.09E-02
Photochemical Ozone	kg NMVOC	2.94E-03	1.47E-02	1.76E-02
Carcinogenic	CTUh	6.98E-10	4.12E-09	4.82E-09
Non-Carcinogenic	CTUh	5.48E-09	3.13E-08	3.68E-08
Respiratory	disease i.	1.31E-07	2.71E-07	4.02E-07
Ozone Depletion	kg CFC-11	9.63E-09	1.06E-08	2.03E-08
Minerals + Metals	kg Sb-Eq	8.27E-08	9.03E-07	9.86E-07
Fossils	MJ	9.51E+00	4.40E+01	5.35E+01
Water	m3 world eq	9.14E-03	3.76E-01	3.85E-01
Land	points	3.29E-05	4.71E-03	4.74E-03

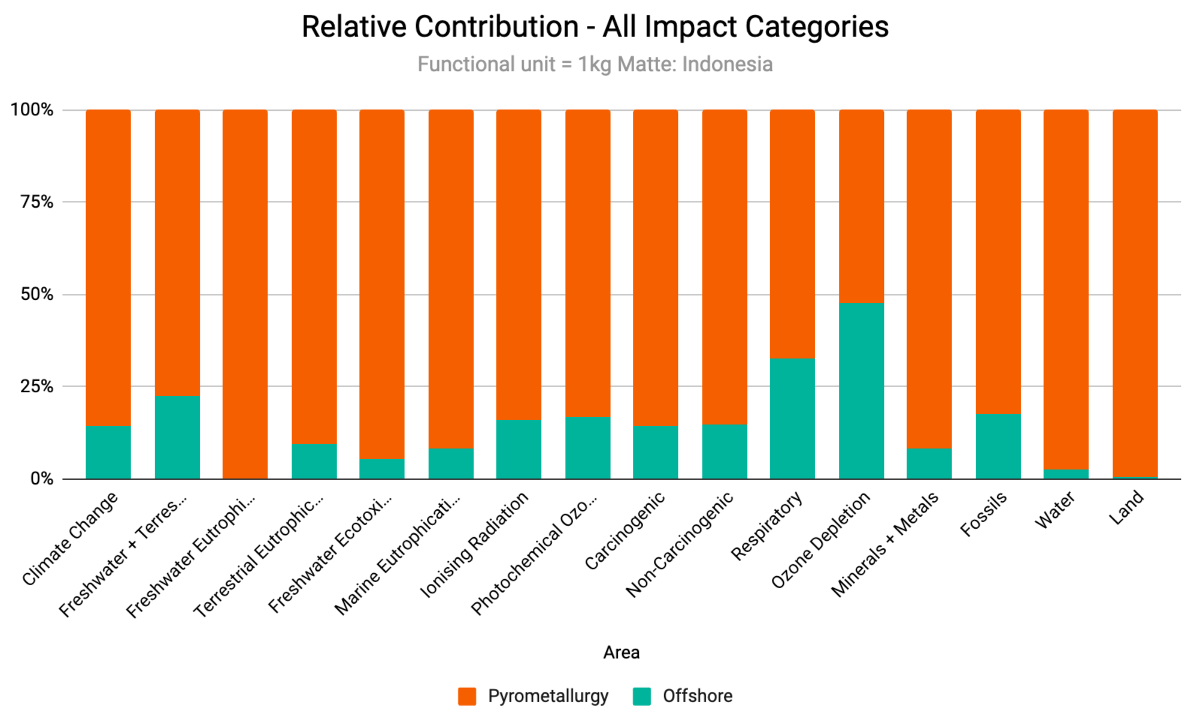


Figure C5: Relative Contribution of all impact categories evaluated in this study per kg of Ni-Cu-Co ; Indonesia.

Table C6. Environmental Impacts per kg Matte – Pyrometallurgy in Japan

Impact Category	Units	Offshore	Pyrometallurgy	Total
Climate Change	kg CO2-Eq	7.70E-01	4.00E+00	4.77E+00
Freshwater + Terrestrial Acidification	mol H+-Eq	1.03E-02	2.87E-02	3.90E-02
Freshwater Eutrophication	kg P-Eq	6.99E-06	1.16E-03	1.17E-03
Terrestrial Eutrophication	mol N-Eq	5.63E-03	3.76E-02	4.32E-02
Freshwater Ecotoxicity	CTU	7.16E-01	7.80E+00	8.51E+00
Marine Eutrophication	kg N-Eq	5.17E-04	3.60E-03	4.12E-03
Ionising Radiation	kg U235-Eq	1.75E-03	2.97E-02	3.15E-02
Photochemical Ozone	kg NMVOC	2.97E-03	1.07E-02	1.37E-02
Carcinogenic	CTUh	7.06E-10	4.22E-09	4.93E-09
Non-Carcinogenic	CTUh	5.54E-09	1.82E-08	2.37E-08
Respiratory	disease i.	1.33E-07	1.58E-07	2.91E-07
Ozone Depletion	kg CFC-11	9.74E-09	1.72E-08	2.70E-08
Minerals + Metals	kg Sb-Eq	8.37E-08	8.69E-07	9.52E-07
Fossils	MJ	9.62E+00	3.23E+01	4.19E+01
Water	m3 world eq	9.24E-03	1.19E-01	1.28E-01
Land	points	3.33E-05	3.08E-04	3.42E-04

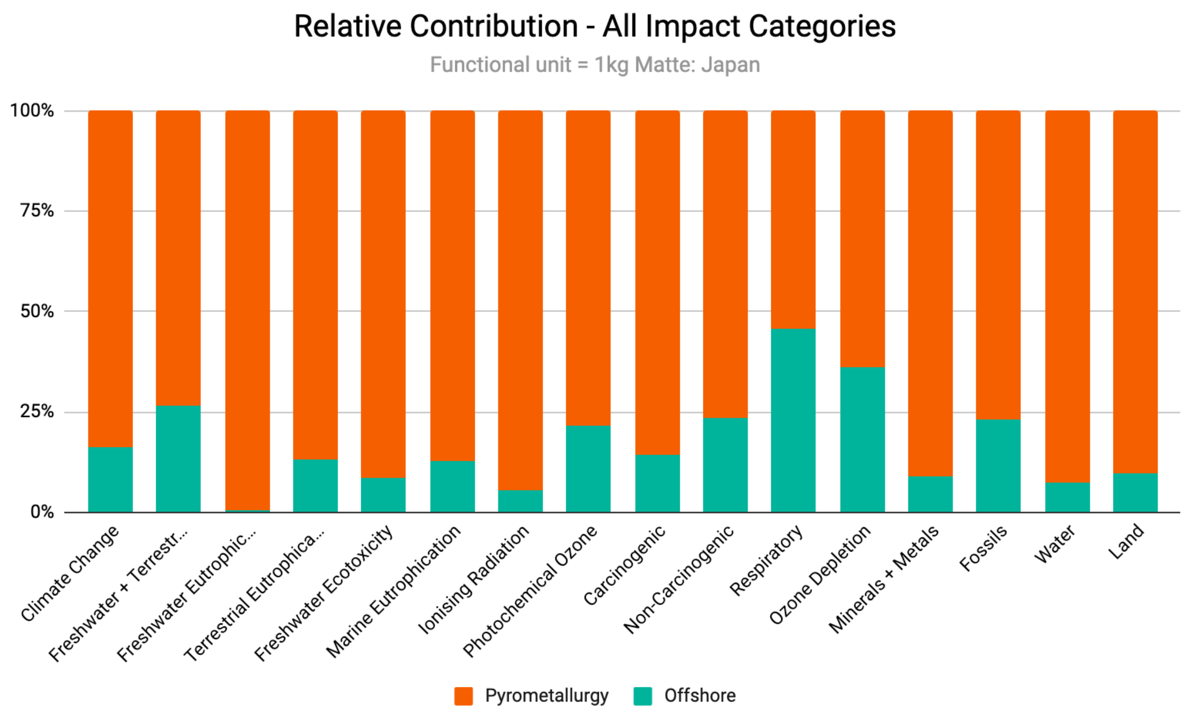


Figure C6: Relative Contribution of all impact categories evaluated in this study per kg of Ni-Cu-Co ; Japan.

Table C7. Environmental Impacts per kg Copper Cathode – Pyrometallurgy in Indonesia, Hydrometallurgy in South Korea.

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	5.23E-01	3.15E+00	4.93E-01	**4.12E+00**
Freshwater + Terrestrial Acidification	mol H+-Eq	4.45E-03	2.68E-02	-2.19E-03	**2.90E-02**
Freshwater Eutrophication	kg P-Eq	4.01E-04	2.41E-03	6.03E-05	**2.87E-03**
Terrestrial Eutrophication	mol N-Eq	5.72E-03	3.45E-02	-9.01E-03	**3.12E-02**
Freshwater Ecotoxicity	CTU	1.26E+00	7.60E+00	-1.25E+02	**-1.16E+02**
Marine Eutrophication	kg N-Eq	5.98E-04	3.60E-03	-1.84E-03	**2.36E-03**
Ionising Radiation	kg U235-Eq	1.07E-03	6.46E-03	2.16E-01	**2.24E-01**
Photochemical Ozone	kg NMVOC	1.73E-03	1.04E-02	-3.52E-04	**1.18E-02**
Carcinogenic	CTUh	4.74E-10	2.85E-09	-6.03E-09	**-2.70E-09**
Non-Carcinogenic	CTUh	3.61E-09	2.18E-08	-1.23E-08	**1.30E-08**
Respiratory	disease i.	3.95E-08	2.38E-07	-2.38E-08	**2.54E-07**
Ozone Depletion	kg CFC-11	1.99E-09	1.20E-08	1.16E-08	**2.56E-08**
Minerals + Metals	kg Sb-Eq	9.69E-08	5.84E-07	-1.25E-04	**-1.25E-04**
Fossils	MJ	5.26E+00	3.17E+01	1.26E+01	**4.96E+01**
Water	m3 world eq	3.79E-02	2.28E-01	-2.76E-01	**-1.02E-02**
Land	points	4.66E-04	2.81E-03	3.42E+00	**3.42E+00**

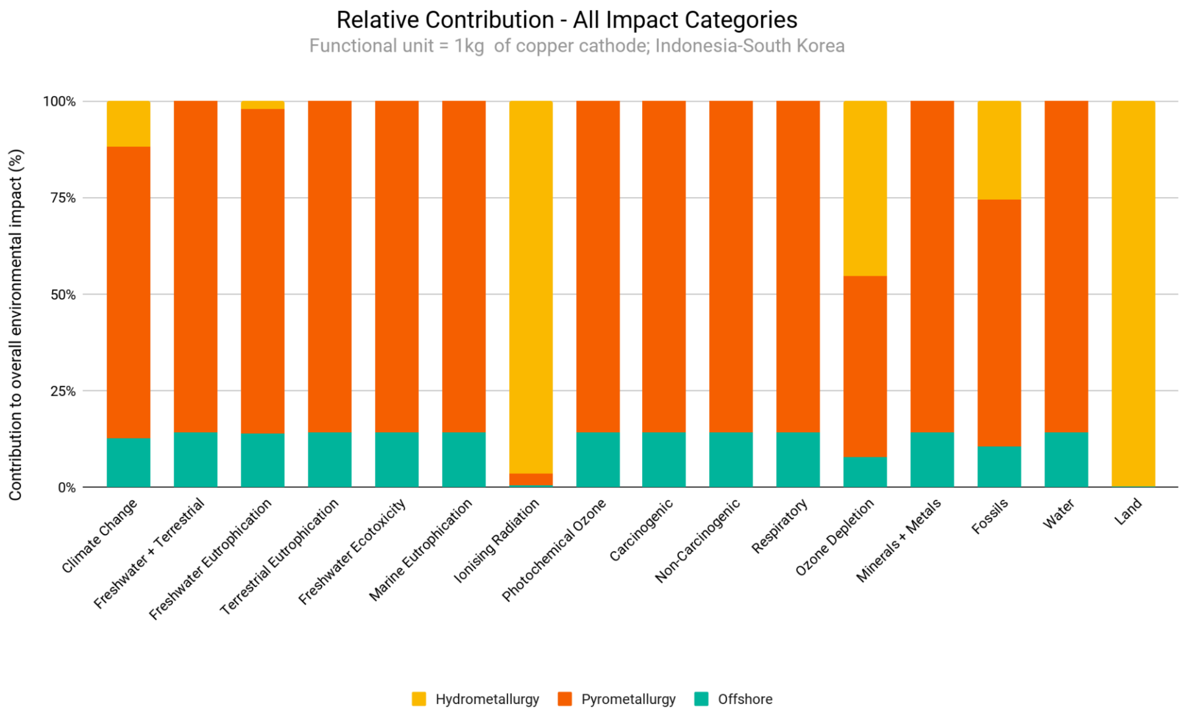


Figure C7: Relative Contribution of all impact categories evaluated in this study per kg of copper cathode ; Indonesia-South Korea

Table C8. Environmental Impacts per kg Copper Cathode – Pyrometallurgy in Japan, Hydrometallurgy in South Korea

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	5.34E-01	2.76E+00	4.93E-01	**3.79E+00**
Freshwater + Terrestrial Acidification	mol H+-Eq	4.37E-03	2.26E-02	-2.19E-03	**2.48E-02**
Freshwater Eutrophication	kg P-Eq	1.30E-04	6.74E-04	6.03E-05	**8.64E-04**
Terrestrial Eutrophication	mol N-Eq	4.83E-03	2.50E-02	-9.01E-03	**2.08E-02**
Freshwater Ecotoxicity	CTU	9.52E-01	4.92E+00	-1.25E+02	**-1.19E+02**
Marine Eutrophication	kg N-Eq	4.60E-04	2.38E-03	-1.84E-03	**1.00E-03**
Ionising Radiation	kg U235-Eq	3.52E-03	1.82E-02	2.16E-01	**2.38E-01**
Photochemical Ozone	kg NMVOC	1.53E-03	7.91E-03	-3.52E-04	**9.09E-03**
Carcinogenic	CTUh	5.51E-10	2.85E-09	-6.03E-09	**-2.63E-09**
Non-Carcinogenic	CTUh	2.65E-09	1.37E-08	-1.23E-08	**4.03E-09**
Respiratory	disease i.	3.26E-08	1.69E-07	-2.38E-08	**1.77E-07**
Ozone Depletion	kg CFC-11	3.02E-09	1.56E-08	1.16E-08	**3.03E-08**
Minerals + Metals	kg Sb-Eq	1.06E-07	5.51E-07	-1.25E-04	**-1.25E-04**
Fossils	MJ	4.68E+00	2.42E+01	1.26E+01	**4.15E+01**
Water	m3 world eq	1.43E-02	7.41E-02	-2.76E-01	**-1.88E-01**
Land	points	3.82E-05	1.98E-04	3.42E+00	**3.42E+00**

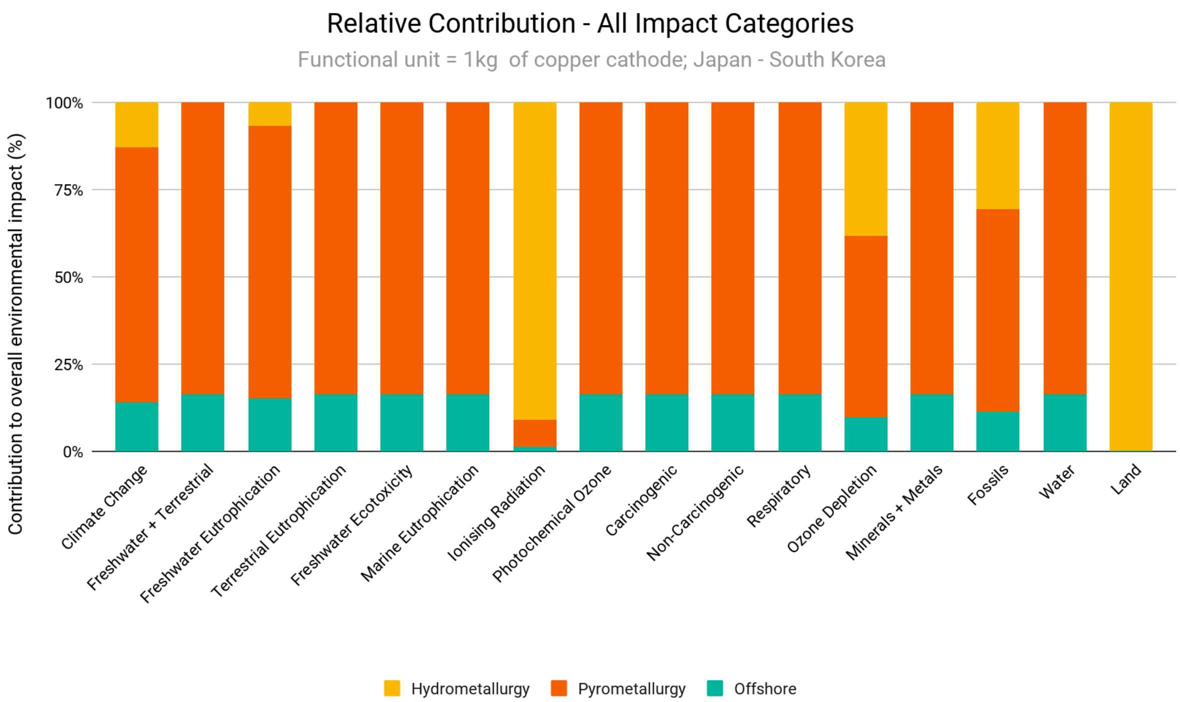


Figure C8: Relative Contribution of all impact categories evaluated in this study per kg of copper cathode; Japan - South Korea

Table C9. Environmental Impacts per kg Co in CoSO4·7H2O – Pyrometallurgy in Indonesia, Hydrometallurgy in South Korea.

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	3.50E+00	2.11E+01	8.11E+00	**3.25E+01**
Freshwater + Terrestrial Acidification	mol H+-Eq	2.98E-02	1.79E-01	-9.25E-04	**2.08E-01**
Freshwater Eutrophication	kg P-Eq	2.69E-03	1.62E-02	1.72E-03	**2.06E-02**
Terrestrial Eutrophication	mol N-Eq	3.83E-02	2.31E-01	4.79E-01	**7.49E-01**
Freshwater Ecotoxicity	CTU	8.46E+00	5.09E+01	-8.24E+02	**-7.64E+02**
Marine Eutrophication	kg N-Eq	4.01E-03	2.41E-02	-8.24E-03	**1.99E-02**
Ionising Radiation	kg U235-Eq	7.19E-03	4.33E-02	1.50E+00	**1.55E+00**
Photochemical Ozone	kg NMVOC	1.16E-02	7.00E-02	8.18E-03	**8.98E-02**
Carcinogenic	CTUh	3.17E-09	1.91E-08	-3.22E-08	**-9.87E-09**
Non-Carcinogenic	CTUh	2.42E-08	1.46E-07	-6.15E-08	**1.09E-07**
Respiratory	disease i.	2.65E-07	1.59E-06	-4.10E-09	**1.86E-06**
Ozone Depletion	kg CFC-11	1.34E-08	8.04E-08	3.14E-07	**4.08E-07**
Minerals + Metals	kg Sb-Eq	6.49E-07	3.91E-06	2.41E-01	**2.41E-01**
Fossils	MJ	3.52E+01	2.12E+02	1.40E+02	**3.88E+02**
Water	m3 world eq	2.54E-01	1.53E+00	1.70E+00	**3.48E+00**
Land	points	3.12E-03	1.88E-02	3.30E+01	**3.30E+01**

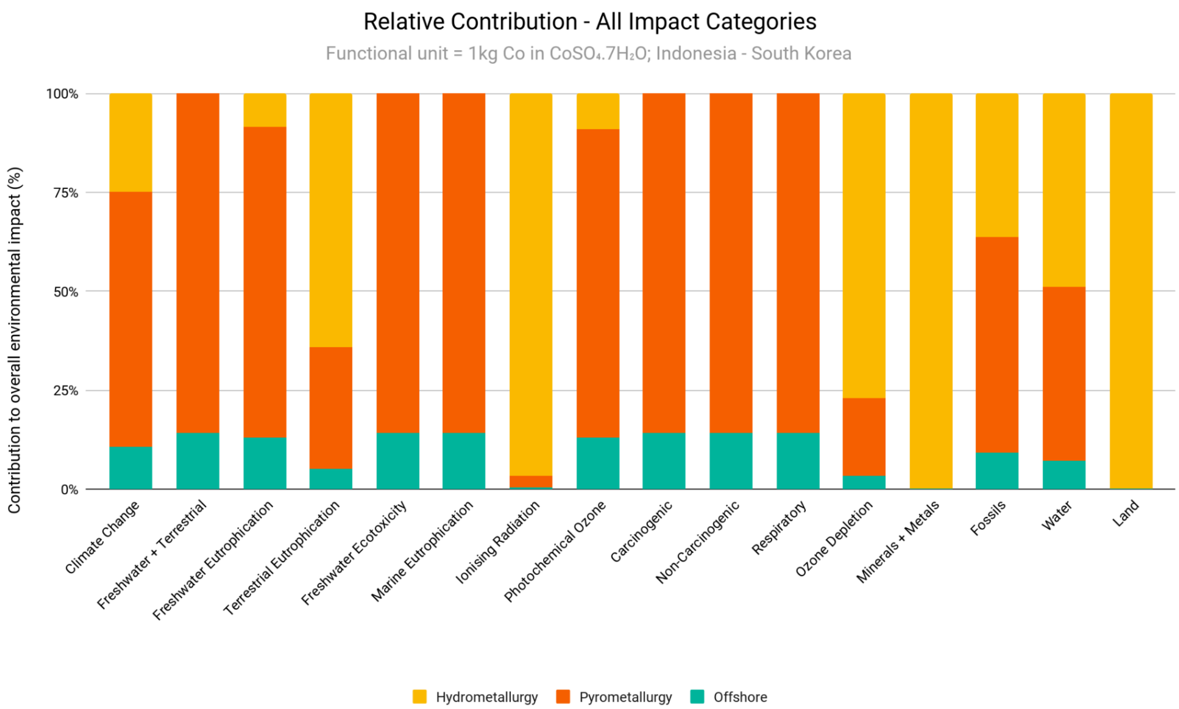


Figure C9: Relative Contribution of all impact categories evaluated in this study per kg of Co in CoSO4·7H2O; Indonesia - South Korea

Table C10. Environmental Impacts per kg Co in $CoSO_4 \cdot 7H_2O$ – Pyrometallurgy in Japan, Hydrometallurgy in South Korea.

Area	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	3.58E+00	1.85E+01	8.11E+00	**3.02E+01**
Freshwater + Terrestrial Acidification	mol H+-Eq	2.93E-02	1.51E-01	-9.25E-04	**1.80E-01**
Freshwater Eutrophication	kg P-Eq	8.73E-04	4.52E-03	1.72E-03	**7.11E-03**
Terrestrial Eutrophication	mol N-Eq	3.24E-02	1.67E-01	4.79E-01	**6.79E-01**
Freshwater Ecotoxicity	CTU	6.38E+00	3.30E+01	-8.24E+02	**-7.84E+02**
Marine Eutrophication	kg N-Eq	3.08E-03	1.60E-02	-8.24E-03	**1.08E-02**
Ionising Radiation	kg U235-Eq	2.36E-02	1.22E-01	1.50E+00	**1.64E+00**
Photochemical Ozone	kg NMVOC	1.02E-02	5.30E-02	8.18E-03	**7.14E-02**
Carcinogenic	CTUh	3.69E-09	1.91E-08	-3.22E-08	**-9.36E-09**
Non-Carcinogenic	CTUh	1.78E-08	9.20E-08	-6.15E-08	**4.83E-08**
Respiratory	disease i.	2.18E-07	1.13E-06	-4.10E-09	**1.34E-06**
Ozone Depletion	kg CFC-11	2.02E-08	1.05E-07	3.14E-07	**4.39E-07**
Minerals + Metals	kg Sb-Eq	7.14E-07	3.69E-06	2.41E-01	**2.41E-01**
Fossils	MJ	3.14E+01	1.62E+02	1.40E+02	**3.34E+02**
Water	m3 world eq	9.60E-02	4.97E-01	1.70E+00	**2.29E+00**
Land	points	2.56E-04	1.32E-03	3.30E+01	**3.30E+01**

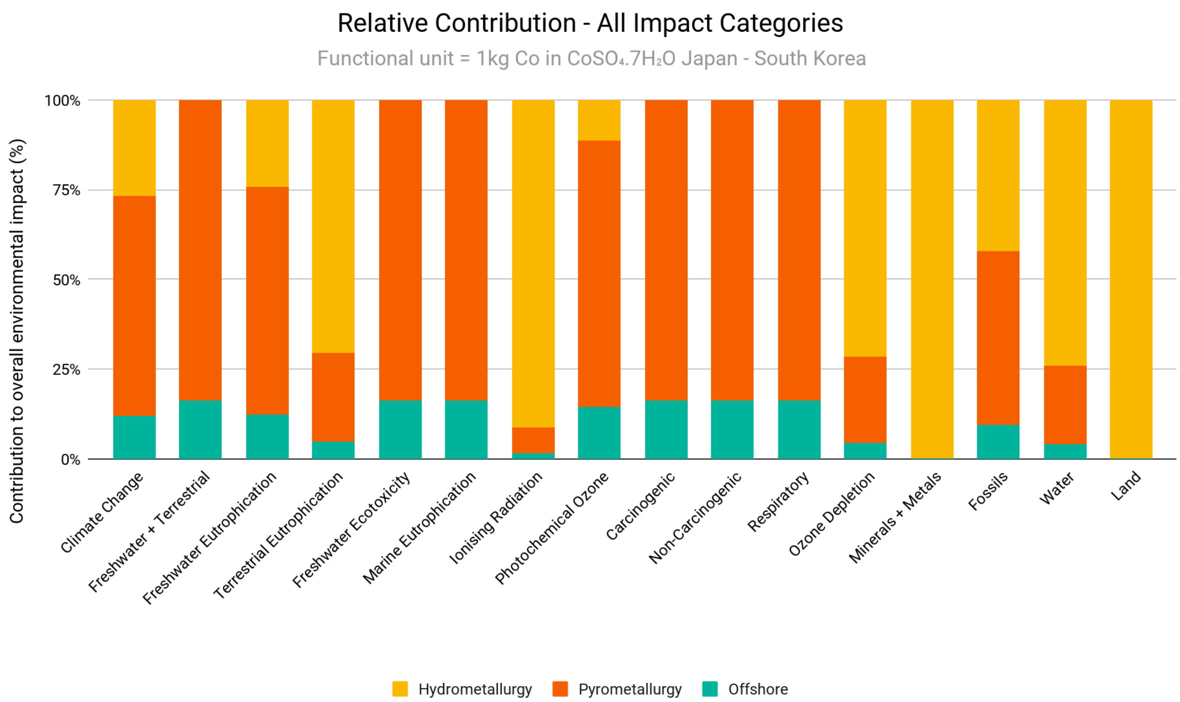


Figure C10: Relative Contribution of all impact categories evaluated in this study per kg of Co in CoSO4·7H2O; Japan- South Korea

Table C11. Environmental Impacts per kg Ni in NiSO4·6H2O – Pyrometallurgy in Indonesia, Hydrometallurgy in South Korea

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	1.18E+00	7.12E+00	2.66E+00	**1.09E+01**
Freshwater + Terrestrial Acidification	mol H+-Eq	1.01E-02	6.05E-02	-7.18E-04	**6.99E-02**
Freshwater Eutrophication	kg P-Eq	9.06E-04	5.45E-03	5.51E-04	**6.91E-03**
Terrestrial Eutrophication	mol N-Eq	1.29E-02	7.79E-02	1.61E-01	**2.52E-01**
Freshwater Ecotoxicity	CTU	2.85E+00	1.72E+01	-2.80E+02	**-2.59E+02**
Marine Eutrophication	kg N-Eq	1.35E-03	8.15E-03	-2.86E-03	**6.64E-03**
Ionising Radiation	kg U235-Eq	2.43E-03	1.46E-02	4.98E-01	**5.15E-01**
Photochemical Ozone	kg NMVOC	3.92E-03	2.36E-02	2.50E-03	**3.00E-02**
Carcinogenic	CTUh	1.07E-09	6.45E-09	-1.13E-08	**-3.80E-09**
Non-Carcinogenic	CTUh	8.17E-09	4.92E-08	-2.16E-08	**3.58E-08**
Respiratory	disease i.	8.93E-08	5.38E-07	-5.77E-09	**6.22E-07**
Ozone Depletion	kg CFC-11	4.50E-09	2.71E-08	1.05E-07	**1.37E-07**
Minerals + Metals	kg Sb-Eq	2.19E-07	1.32E-06	8.13E-02	**8.13E-02**
Fossils	MJ	1.19E+01	7.16E+01	4.63E+01	**1.30E+02**
Water	m3 world eq	8.56E-02	5.16E-01	5.52E-01	**1.15E+00**
Land	points	1.05E-03	6.35E-03	1.08E+01	**1.08E+01**

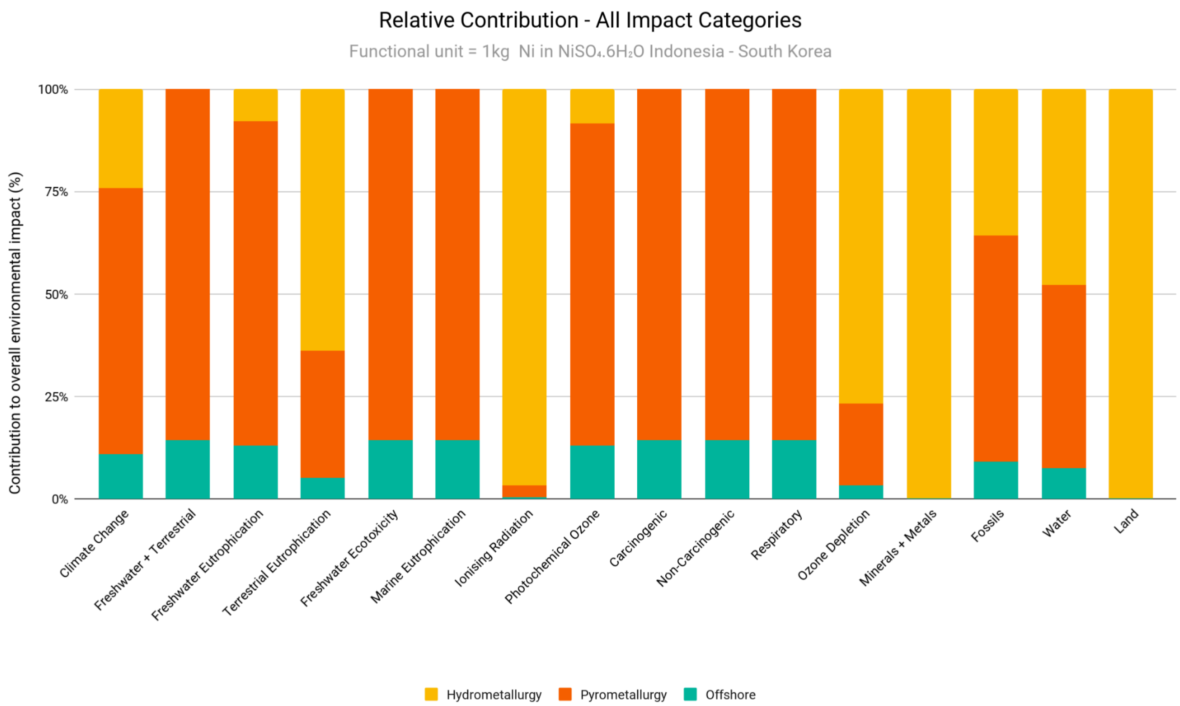


Figure C11: Relative Contribution of all impact categories evaluated in this study per kg of Ni in NiSO4·6H2O; Indonesia- South Korea

Table C12. Environmental Impacts per kg Ni in NiSO4·6H2O: Pyrometallurgy in Japan, Hydrometallurgy in South Korea

Impact Category	Units	Offshore	Pyrometallurgy	Hydrometallurgy	Total
Climate Change	kg CO2-Eq	1.20E+00	6.24E+00	2.66E+00	**1.01E+01**
Freshwater + Terrestrial Acidification	mol H+-Eq	9.83E-03	5.11E-02	-7.18E-04	**6.02E-02**
Freshwater Eutrophication	kg P-Eq	2.93E-04	1.52E-03	5.51E-04	**2.37E-03**
Terrestrial Eutrophication	mol N-Eq	1.09E-02	5.65E-02	1.61E-01	**2.28E-01**
Freshwater Ecotoxicity	CTU	2.14E+00	1.11E+01	-2.80E+02	**-2.66E+02**
Marine Eutrophication	kg N-Eq	1.04E-03	5.39E-03	-2.86E-03	**3.56E-03**
Ionising Radiation	kg U235-Eq	7.93E-03	4.12E-02	4.98E-01	**5.47E-01**
Photochemical Ozone	kg NMVOC	3.44E-03	1.79E-02	2.50E-03	**2.38E-02**
Carcinogenic	CTUh	1.24E-09	6.45E-09	-1.13E-08	**-3.63E-09**
Non-Carcinogenic	CTUh	5.97E-09	3.10E-08	-2.16E-08	**1.54E-08**
Respiratory	disease i.	7.34E-08	3.81E-07	-5.77E-09	**4.49E-07**
Ozone Depletion	kg CFC-11	6.80E-09	3.53E-08	1.05E-07	**1.47E-07**
Minerals + Metals	kg Sb-Eq	2.40E-07	1.25E-06	8.13E-02	**8.13E-02**
Fossils	MJ	1.05E+01	5.48E+01	4.63E+01	**1.12E+02**
Water	m3 world eq	3.23E-02	1.68E-01	5.52E-01	**7.52E-01**
Land	points	8.60E-05	4.47E-04	1.08E+01	**1.08E+01**

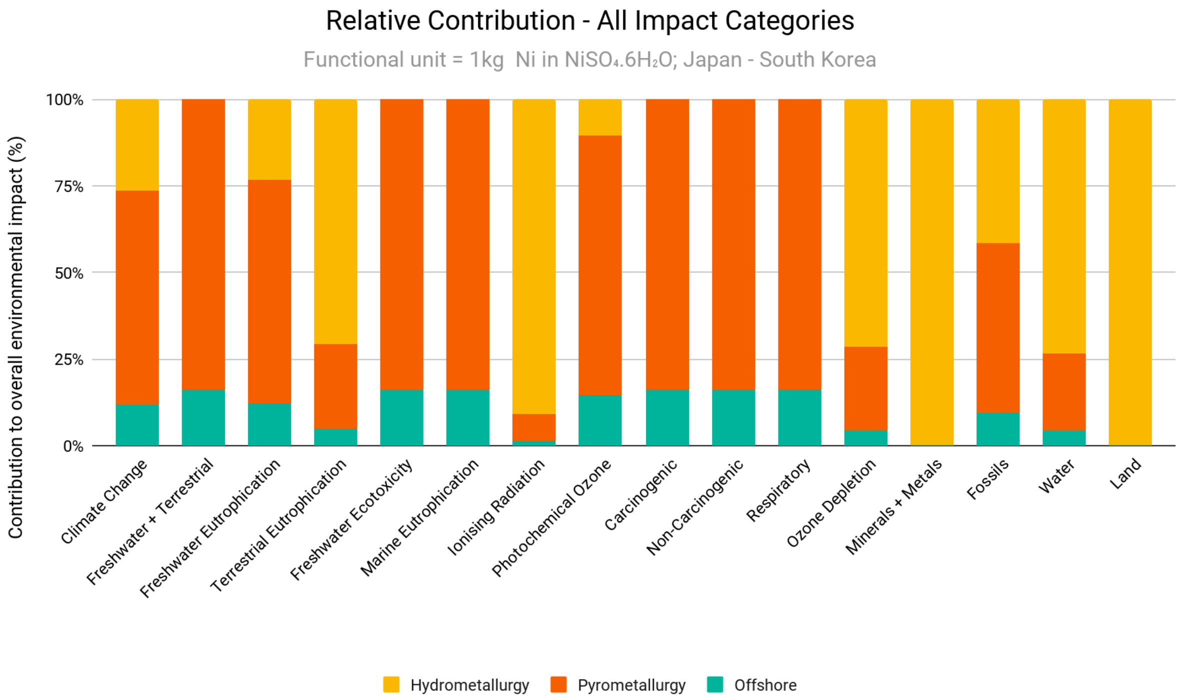


Figure C12: Relative Contribution of all impact categories evaluated in this study per kg of Ni in NiSO4·6H2O; Indonesia- South Korea

11. Appendix C– Findings and Recommendations from the Critical Panel Review.

Reviewers: Quentin Dehaine (GQ), Joris Šimaitis (JS) and Irdanto Saputra Lase (ISL)

"Type of comment" may be referring to "general" (ge), "editorial" (ed) or "technical" (te)

Initials	Index	Page	Section/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
QD	1	1	Front Cover / Title	Ge	TMC's polymetallic nodule sounds off. CCZ's polymetallic product sounds more appropriate. Since no deep-sea mining and mineral processing project is in operation, this LCA is prospective Also, the title should reflect that two distinct production routes are assessed	Suggestions: PROSPECTIVE LIFE CYCLE ASSESSMENT STUDY OF TWO PRODUCTION ROUTES FOR VARIOUS PRODUCTS FROM POLYMETALLIC NODULES	In the context of LCA, 'prospective' LCA (pLCA) has a very specific meaning and methodology underpinning it. This particular study does not fall into that category. Now project 1 has been removed from the report and so only one singular "production route" is presented now. Instead the report title has been modified to "LIFE CYCLE ASSESSMENT OF VARIOUS PRODUCT OUTPUTS FROM THE NORI-D POLYMETALLIC NODULES PROJECT"
QD	2	2	Our Statement	Ge	To produce a life cycle assessment for the production of a silicomanganese ~~produced~~ from the manganese silicate made in TMC's pyrometallurgy operations. > A bit reductive considering that upstream (mining/processing) is also included to some extent as well as two different options for multiple co/byproducts production	Update statement accordingly	The final paragraph of the Our Statement section has been modified to say the following: "The Metals Company (TMC) commissioned Minviro Ltd as an LCA practitioner in August 2023 to conduct an LCA quantifying the environmental impacts associated with the production

							of manganese silicate (MnSiO3), Ni-Cu-Co matte, copper cathode, nickel sulphate hexahydrate (NiSO4·6H2O), and cobalt sulfate heptahydrate (CoSO4·7H2O) from polymetallic nodules. The results of this study are for internal and external use and are intended to be communicated to the public.”
QD	3	4 (and 24)	Executive Summary	Ed/Te	“Unlike terrestrial mining, which requires the removal of overburden and waste rock, polymetallic nodules lie unattached on the seafloor, eliminating the need for extensive land disturbance or waste management.” > This is a bit of an overstatement, sounds a bit subjective and, with no actual nodule continuous mining operation to back it up, is unsubstantiated. Ok, no overburden but still sediment plumes created by nodule collection (like dust clouds in terrestrial mining) and sediments collected along with the nodules that will need to be disposed off (generating a mid-water plume). Research suggests that these plumes don't spread out over a wide area, so it is a local impact mostly.	Ponder this statement, highlight the absence of historical data to back up this statement, add reference to scientific publications to support the claims about the potentially limited impacts and mention that the current consensus is that further research into the local impacts of nodule mining is still needed. Likewise for project description p24.	This point has been misinterpreted. This statement does not refer to the sediments that may be disturbed under the sea surface. It purely addresses the fact that nodule extraction does not lead to the formation of overburden like with terrestrial mining.
QD	3	5	Executive Summary	Ed	“The primary goal of this LCA is to provide TMC with insights to guide emissions reduction Strategies” > A bit reductive, many other impact categories assessed	Replace *emission reduction* by *environmental impact reduction*	Done. Text now reads: “The primary goal of this LCA is to provide TMC with insights to guide environmental impact reduction strategies and enhance the sustainability of the metal production process.”

QD	4	6	Executive Summary	Te/Ed	“In both projects, the ‘cradle’ is the deep sea mining of the polymetallic nodules where the impact of producing and burning the marine fuel oil used in the process is quantified.” I’m puzzled with the system boundary and whether it can be considered ‘cradle’. The “mining” of deep-sea nodules can be roughly broken down into 3 stages: 1. Nodule collection by remote-controlled vehicles operating at the seabed/deep sea interface, 2. Nodule(+/- sediment) in slurry transfer by a riser to the surface, 3. Nodules discharge, dewatering/cleaning in Production Support Vessel (PSVs) before transfer to a transport vessel In this study, the impact assessment only considers impacts associated with burning fuels at stage 3 and not impacts associated with stages 1-2 (for lack of framework).	This limitation should be further clarified here by specifying what is meant by deep sea mining, which stages and which impacts or omitted or included for each of these steps.	You are incorrect. The marine fuel used considers the entire nodule collection process and transshipment of the nodules. The fuel use is for the production vessels, production vessel compressor, supply vessel, transhipment vessels, bulk carriers, and support vessels. It is not only for nodules discharge.
QD	5	6	Executive Summary/Fig1	Te	Labelling slag as a product does not seem right. It only a product if it is used or sold as such. This has implications for system expansion/allocations. Same question for ammonium sulphate A proper detailed plan to accommodate these streams must be given to show how TMC plans to del with them and not just getting the carbon credits	Clarify the status of the slag and ammonium sulphide outputs and justify system expansion by detailing the plan to accommodate these streams (eg slags used as construction material, ammonium sulphide for fertilisers).	In this product system, the converter slag and ammonium sulfate are considered as being co-products, hence system expansion has been applied in both cases. And it is for this reason that both appear in Figure 1. In Table 3 (and later in Table 5) a new row has been created with the heading “Other co-products”. Here the following details have been included:

							"Ammonium sulfate (assumed to be substitute globally produced ammonium sulfate used in the Chemicals and Agriculture Industry) and converter slag (assumed to be used as an aggregate material in road construction)"
QD	7	7	Executive Summary	Ed	"As shown in Section 7.1, the climate impact per kg of SiMn is 7.04 kg CO2 eq ~~per kg SiMn~~." "TMC's MnSiO3 production contributes **to** 1.32 kg CO2 eq, while the conversion of MnSiO3 to SiMn adds 5.72 kg CO2 eq." "Scope 1, 2, and 3 emissions per kg of SiMn are 1.12 kg CO2 eq, 0.02 kg CO2 eq, and 5.90 kg CO2 eq ~~per kg SiMn~~, respectively."	Update text as suggested	Correction made
QD	8	8	Executive Summary	Ed	"In this scenario, the downstream process contributed a larger share of the emissions (6.48 kg **CO2** eq)," > font issue with CO2	Update font/Style	Formatting corrected
QD	9	9-10	Executive Summary: Table 4-5	Ed	A lot data is shown here. While the numbers must be given somewhere in a table, it may not be best placed here. Since every Impact category has a different unit, there is no advantage to using a table. We need to compare columns (cases/products) so it may be best to present the results in Figures, one of react table, with one subplot (bar chart) for each category	Replace table 4 and 5 by figures (suggestion)	Suggestion not accepted The inclusion of figures in place of tables, given the number of functional units studied, would make for a very expansive executive summary section. This is why a summary table of results was opted for.
QD	10	24	4.2.2.2 / Table 6	Te	For project 2, depending on the answer to comment #5. Either remove ammonium sulphate or add slags Mention here the alternative locations for MnSi3 production (Malaysia, India) and Malaysia for MnSi	Update table text	In Table 3 and Table 5 a new row has been created: "Other co-products". Here the following details have been included: "Ammonium sulfate (assumed to be substitute globally produced ammonium sulfate

							used in the Chemicals and Agriculture Industry) and converter slag (assumed to be used as an aggregate material in road construction)” Tables also clarify details on the various locations where each stage of the process is performed.
QD	11	26	4.2.2.2	Ed	Table 6 should be table 7	Update table numbering throughout the document	Numbering of figures and tables have been checked and updated throughout.
QD	12	28	4.3	Ed	Figure 3. Labels for slag should be more specific (eg converter slag) to avoid confusion with Mn-rich slag (TMC’s manganese silicate product)	Update Figure	Project 1 has been removed so it is no longer necessary to make this distinction in the diagram. With this said, the slag is now referred to as ‘converter slag’ in the figure and other areas of the report.
QD	13	29	4.3.1 System Boundary Project 1	Ed	For the comparative scenario, no details are given about the system (locations of the different stages, Mn ore type, etc)	Add details about the comparative case study	Project 1 now removed from the report
QD	14	30 /31	4.3.1 /2System Boundary Project 1 /2	Te	Why is the transportation of manganese silicate to China or Malaysia omitted? This item would change significantly depending on where the first pyro stage is happening (Texas vs China) for project 1 or hydro stage for project 2 The following items are only listed in the omissions table for one of the two projects. There should be in both (or grouped as one item): • Option 1: Emissions to air, land and water associated with the deposition of tailings and waste sludges in tailings ponds/piles.	Justify this omission and update table 7 and 8	The distance in transport from Japan to Indonesia is roughly 5000 km, and the difference in the values are 0.76 to 0.77 kg CO2. The distance from Japan to SK is 1,000 km and therefore the impact from the marine fuel oil would be negligible (<0.01 kg CO2). This is also the case for transport from Indonesia to SK. This is compounded by the fact that the matte is significantly more

					• Option 2: "Sediment and other impacts from dislodging of nodules on the seafloor" The latter should specify that *emissions to water (and land/seabed)* from discharging sediments.		lightweight than the polymetallic nodules. Option 1 is applicable to project 2, and project 2 is now the only project included in the report. As for Option 2, there is no tailing produced in this system so therefore it is not included in the current table. Option 2 has now been replaced with the following text: "Emissions to water and land/seabed from sediment discharge and other impacts from dislodging of nodules on the seafloor."
QD	15	32	4.4.2	Ed	"a silicate rich in MnSiO3" > wrong wording Also, this product is sometimes referred to as Mn-rich slag or MnSi-rich slag, which it is but these different terms can be confusing	Replace by "manganese silicate product" here and elsewhere in the document	This product is not a typical Mn rich slag. It is pre-reduced and has a higher Mn content than what is typically seen. The engineers and head of onshore development prefers the term "silicate rich in Mn" or TMC's MnSiO3 as those terms are more accurate.
QD	16	33	4.4.2.1	Ed	" a silicate rich in manganese (TMC's MnSiO3)" > here again wording issue	Replace by a Mn-rich slag (TMC's manganese silicate product)	See above comment.
QD	17	33	4.4.3	Ed/Te	The description of the hydrometallurgical circuit needs revision. I believe it is taken from TMC's technical report. They are some approximations and oddities in the text. A few examples: • "The circuit then follows a sulphuric acid leach	The description of the hydrometallurgical and electrochemical processes should be improved after a technical change. Some details may be	The sentences have been amended. "The circuit follows an Al-POX-SX-EW" flow sheet has been implemented. You are correct. copper is

						flowsheet" > a "sulphuric acid flowsheet" is not a circuit type. It's just the acid used. The circuit is actually much more complex. Here it could be labelled "AL-POX-SX-EW" ● "A two-stage leach is used to produce copper cathode" > This is wrong Cu cathode is produced from EW ● "The pulped matte is then pumped to the first stages of atmospheric leaching where oxygen and spent electrolyte from electrowinning leach the matte." > What about the sulphuric acid ? ● "The upgraded matte then proceeds to pressure leaching" > It's pressure oxidative leaching (POX) and "upgraded matte" is a bit misleading here – AL residue is more correct ● "In extraction, the iron-free solution first contacts an organic solution (Cyanex-272) that selectively removes cobalt via mixer tanks. After contacting the organic, the aqueous solution is separated using settler tanks" > This sentence needs revision. The terminology used (contact?) is not appropriate.	removed, and the description should be kept general with references to a flowsheet if describing the process and mechanisms is an issue. I don't think detailed descriptions are needed here.	electrowon from the electrolyte. Yes, the matte is leached with spent electrolyte, sulphuric acid, and oxygen. Al residue makes it sound like it is a waste product (like other residues within the circuit. Upgraded matte is more accurate for this flowsheet. This has been kept the same. The last point has been left unchanged. Since the liquids are immiscible, they only come into **contact** with each other (and are not mixed) such that the cobalt can migrate to the solution where it is most soluble.
QD	18	38	4.5			When discussing the slags please specify which slag you are talking about (i.e. converter slag, from which pyro stage) Project 2 allocations do not include the slags	Specify the type of slag discussed and include slags allocation in Project 2	"converter slag" has been added to the table summarising the methods of co-product management

							applied in this project (Table 8) Throughout the report the slag produced is referred to as "converter slag"
QD	19	42	5.1. Data Collection and Calculation	Ed	For the foreground data, please reference the technical reports used and provide a link in the references list if they are public. This will be useful to judge the quality of the data. For instance, if the data related to pyro and hydro operations were gathered from the 2021 technical report by AMC then the term "piloted metallurgical flowsheet" may not be appropriate because the report only presents, beside a literature review of similar process with distinct ores, only pyrometallurgical lab-scale tests. So it would be useful to expand here a bit on the foreground data provided by TMC, and for each stage of the flowsheet specify if it's coming from literature, lab-scale or pilot-scale tests. A mention of the volumes/masses tested would help support these claims as people have different understanding of what pilot scale means.	Expand on the foreground data, make explicit reference to TMC's public or internal reports	The second paragraph now specifies the following: "Foreground data, relating to offshore operations, pyrometallurgy and hydrometallurgy processes were sourced from TMC's internal NORI-D project PFS (October 2024) and offshore data from SK-1300 compliant NORI Initial Assessment (March 2021)." Whilst the PFS is not publicly available the NORI initial assessment is available, and so the reference (https://www.sec.gov/Archives/edgar/data/1798562/000121390021033645/fs42021a2ex96-1_sustainable.htm) has also been provided. It has also been included as a note in Table 3 that the PFS is not publicly available.
QD	20	43/46	5.2 Life Cycle Inventory Data - Project 1	Te	In Table 11 and 14: • Water-sediment nodules mix should be listed as input • Sediment water/mix as an output • Electrode paste amount missing • MnSi rich slag should be replaced by "manganese silicate		Project 1 removed from the report

					(product)" for both pyro stages - Replace "Slag" by "converter slag" - Ni-Cu-Co Matte is not fed in the next pyro stage (I believe this is misplaced and should have been for the manganese silicate stream) - No unit for CO/SO2 emissions (1st pyro stage)		
QD	21	44	5.2.1. Sensitivity Analysis	Te	In Table 12, the area affected is MnSiO3 production not MnSi		Project 1 removed from the report
QD	22	50	5.4.1. Data Quality Assessment Results		**Technological representativeness:** "LCI data for the Offshore, Pyrometallurgy (MnSiO3 production) and Hydrometallurgy steps was collected during the course of TMC's pilot scale operation and so it is technologically representative" > As discussed in comment #19 the extent to which is stage of the flowsheet was indeed tested at the pilot-scale must be clarified. The point, plus the reliance on literature data for the SiMn production while TMC's MnSiO3 product does not fit any existing benchmark for this product (cf TMC's 2021 TR), justify more a "good" grade according to the grading guidelines		Project 1 has been removed from the report However, this section of Table 12 now says (in reference to Project 2): *"Project scenario based from TMC's internal NORI Project PFS (October 2024) and onshore technical data was taken from SK-1300 compliant NORI Project Initial Assessment (March 2021).[47] However a PFS has a lower associated degree of confidence than an FS, and even lower than operational data. As such, it has been given a rating of fair."*
QD	23	52	6.1. Assumptions: Project 1	Te	Any claim or assumption about electricity grid mix scenarios must be somehow backed up by evidence (data) if it represents a scenario close to what already exists or in the case of this purchase agreement some kind of proof that this agreement exists (press release?)	Update text accordingly and justify the assumption	Project 1 removed from the report

					This is even more important here where a 100% wind power mix is assumed as this would influence the results dramatically.		
QD	24	53	6.1. Assumptions: Project 1	Ed	Allocation for NiCo-Cu Matter is missing. The specific energy values assumed for the electric arc furnace required for the conversion of TMC's MnSiO3 to SiMn seem ok but it must be justified.	Add product allocation for the matte The specific energy values must be justified	Project 1 removed from the report
QD	25	57	7.1.1. Climate Change by Stage	Ed/Te	Here the actual contribution of each stage (mining, MnSiO3/Matte production, SiMn production etc) is not shown despite what the text and caption for Figure 5 claim. The labels on the X-axis must be more explicit and specifically refer to the stage and the contributor. Also, you use alternatively abbreviations like for direct emissions / DE	Add here (and for project 2) the actual contribution of each stage in a separate figure or by colouring the bars according to the stage Update here and after the labels for each bar chart	Project 1 removed from the report
QD	26	60	7.1.3. Climate Change Scope Emissions	Te	It is mentioned that TMC's vehicle fleet onshore will be entirely EVs hence the close to 0 scope 2 emissions. How realistic is that? It's not only passenger vehicles, but also trucks, slag haulers, tapping vehicles and other utility vehicles – these are not EVs	Provide details and justifications about the assumption that every vehicle will be EV with reference to the type of vehicle (passenger or utility) and for the latter some reference to models	Project 1 removed from the report
QD	27	74	7.2.5. Functional unit: 1kg cobalt in cobalt sulfate	Ed	Why highlight the text in bold here (main contributors) and not elsewhere?	Harmonize formatting	Formatting is now consistent
	28	82-83		Te	Here, one of the main comparison points, i.e. terrestrial mining vs offshore nodule mining is overlooked compared to the downstream processing The contribution from each stage (mining, transport, RKEF, SiMn conversion) should be shown in Figs 24 and 25	Add a brief discussion on the comparison of the impact of mining vs nodules Update Figs 24 and 25	Project 1 removed from the report
QD	29	92	9.2. Sensitivity Analysis - Project 2	Ed	"The results are presented in Figures X - X."	Update Figures number	As part of the report revamp (which has largely been guided by the requirements of the client, this section has been

							removed from the report entirely.
QD	30	112	11. References	Ed	As mentioned earlier some references to public or confidential TMC's technical reports from which you got the data should be listed here	Update references list	The link to the NORI initial assessment is publicly available, and so has been added to the reference list. References relating to the economic data used for allocation have also been added.
ISL	31	Cove r		Ed	Name of reviewers, change from Laura to Joris		Corrected to Joris Šimaitis
ISL	32	(Pg 2)	Our Statement	Ed	The Metals Company (TMC) commissioned Minviro Ltd. as an LCA practitioner in August 2023 to produce a life cycle assessment for the **"production of a silico-manganese"** produced from the manganese silicate made in TMC's pyrometallurgy operations.	There are two projects in the report, with 2 system boundary. It is important to mention all products in the Statement page, incl. Copper Cathode, $CoSO_4$, and $NiSO_4$ from Project 2 via pyro-hydrometal lurgy	Project 1 has now been removed from the report. The final paragraph of the executive summary has been modified to say the following: "The Metals Company (TMC) commissioned Minviro Ltd as an LCA practitioner in August 2023 to conduct an LCA quantifying the environmental impacts associated with the production of manganese silicate ($MnSiO_3$), Ni-Cu-Co matte, copper cathode, nickel sulphate hexahydrate ($NiSO_4 \cdot 6H_2O$), and cobalt sulfate heptahydrate ($CoSO_4 \cdot 7H_2O$) from polymetallic nodules. The results of this study are for internal and external use and are intended to be communicated to the public"
ISL	33	(Pg 4)	Exec Summary	Te	TMC aims to minimise waste generation by producing useful **"by-products"**, thereby reducing the need for large-scale waste or tailings facilities	Make it clear what products are referred here, and use the correct terminology.	A more general approach to this and instead the word "products" has been used now.

					Comment By-product as in 'waste'? Or co-product as in 'valuable metals'?	e.g., Are you referring to Slag? Or Copper cathode? Are they Co-product or by-product?	This can encompass the co-products (manganese silicate, cobalt sulfate, nickel sulfate and copper cathode) and by-products produced in the system (ammonium sulfate and converter slag)
ISL	34	(Pg 4)	Exec Summary	Te	Project 2: which aims to quantify the environmental impacts associated with the production of manganese silicate (MnSiO3), **"Ni-Cu-Co matte"**, ... Comment Ni-Cu-Co matte is an intermediate product for NiSO4, CoSO4, etc products, as clearly shown in the system boundary. When Ni-Cu-Co matte is selected as the FU (i.e., 1 kg of Ni-Cu-Co matte), do you consider the environmental impact of downstream processing of NiSO4, CoSO4, Cu cathode, etc?	Add extra information or notes saying that the downstream process are excluded when Ni-Cu-Co matte is selected as the FU	I have now included this as a note in the summary Table 3, instead of in the main body of text. At the foot of the table it now reads: "** When the functional unit of 1kg Ni-Cu-Co matte used, note that the environmental impacts associated with downstream processes are excluded - namely the transport and hydrometallurgical processing of the Ni-Cu-Co matte."
ISL	35	(Pg 5)	Table 3	Te	In project 2, are we producing Nickel Sulfate Monohydrate? Not Nickel Sulfate Hexahydrate as in precursor for CAM?	Check for any typo or missing information NiSO4.H2O or NiSO4.6H2O ?	It should be nickel sulfate hexahydrate (NiSO4.6H2O) This correction/clarification has now been made throughout the report.
ISL	36	(Pg 5)	Table 3	Te	**Ni-Co-Cu matte** is considered as marketable products in Project 1, but it is not considered as marketable product in Project 2 However, Ni-Cu-Co matte is selected as one of the FUs How did you apply the allocation for non-marketable product of Ni-Cu-Co matte as FU and MnSiO3 as co-product in Project 2?	Check for any typo or missing information Or add extra notes or information how allocation was done for non-marketable product	Project 1 now removed from the report
ISL	37	(Pg 5)	Table 3	Te	Comparison analysis was done for SiMn in Project 1 Which supply chain is this SiMn from terrestrially sourced ore? What is the ore type and	Consider to add more information on the supply chain for SiMn mining from terrestrial ore	Project 1 now removed from the report

					processing route? Pyro, hydro, or a combination of pyro-hydro?		
ISL	38	(Pg 6)	Figure 1	Te	In Project 2, "**dry polymetallic nodules processed**" is selected as one of the FUs This (intermediate) product must be reflected in the system boundary Figure 1	Add "dry polymetallic nodules processed" in the system boundary diagram, that is distinct from "wet" polymetallic nodules from the seabed	The purpose of the diagram isn't to show/represent the functional units. It is there to provide a process overview, to aid the reader. Furthermore, it doesn't need to say dry because, what the FU of 1kg refers to is the weight of the polymetallic nodules but in their dry weight content. The nodules themselves, where indicated on the diagram, are not actually dried offshore.
ISL	39	PG 6	Figure 1	Te	In project 2, are we producing Nickel Sulfate Monohydrate? Not Nickel Sulfate Hexahydrate as in precursor for CAM?	Check for any typo or missing information NiSO4.H2O or NiSO4.6H2O ?	Corrected to nickel sulfate hexahydrate (NiSO4.6H2O)
ISL	40	(Pg 7)	Methodology	Ge	Two ecoinvent database are used for Project 1 and Project 2 Why?	Give extra information why two databases are used in Project 1 and Project 2	Project 1 has now been removed from the report.
ISL	41	Pg 7	Methodology	Ed	This approach satisfied the objectives of the study by providing the environmental impacts associated with the production of MnSiO3, SiMn (and the comparison to SiMn produced from terrestrial ores), copper cathode, **nickel sulfate**, and **cobalt sulfate**, ... Comment It is ok to call just nickel sulfate and cobalt sulfate. But a short sentence saying that this nickel sulfate is actually NiSO4.6H2O and cobalt sulfate is actually CoSO4.7H2O is needed when these terms are introduced for the first time	This approach satisfied the objectives of the study by providing the environmental impacts associated with the production of MnSiO3, SiMn (and the comparison to SiMn produced from terrestrial ores), copper cathode, nickel sulfate hexahydrate (will be called "nickel sulfate" from now onwards), and	For consistency, Throughout the report nickel sulfate hexahydrate and cobalt sulfate hexahydrate are now represented by their chemical formulae (NiSO4.6H2O and CoSO4.7H2O)

						cobalt sulfate heptahydrate (will be called “cobalt sulfate” from now onwards), ...	
ISL	42	Pg 7	Climate Change – Project 1: SiMn Production (Comparison Scenario)	Ed	**In this scenario**, the downstream process contributed a larger share of the emissions (6.48 kg CO2 eq), as **TMC’s pre-reduction step**, which helps reduce emissions earlier in the production process, was absent. Comment Is this number 6.48 refer to TMC base-case or SiMn primary production? Which one is TMC’s pre-reduction step? Is this pyromet converting MnSiO3 to SiMn?	Consider to add information to bring clarity to the scenario and processing stage mentioned in the text (TMR pre-reduction = 2nd Pyromet process converting MnSiO3 to SiMn?)	Project 1 has now been removed from the report.
ISL	43	Pg 8	Climate Change – Project 2: Cobalt in Cobalt Sulfate (Base-Case)	Te	As shown in Section 7.2.5, the climate change impact per kilogram of cobalt in **cobalt sulfate** is 25.58 kg CO2 eq when ... Comment Is this Co in CoSO4.7H2O? with ~21% Co content	Add extra information about the Co content in cobalt sulfate heptahydrate	“(21% Co)” inserted into the heading. For consistency, Throughout the report nickel sulfate hexahydrate and cobalt sulfate hexahydrate are now represented by their chemical formulae (NiSO4.6H2O and CoSO4.7H2O)
ISL	44	Pg 8	Climate Change – Project 2: Cobalt in Nickel Sulfate (Base-Case)	Te	As shown in Section 7.2.6, the climate change impact per kilogram of nickel in **nickel sulfate** is 11.55 kg CO2 eq when Comment Is this Ni in NiSO4.6H2O? with ~22% Ni content	Add extra information about the Ni content in nickel sulfate hexahydrate	“(22.4% Ni)” inserted into the heading. For consistency, Throughout the report nickel sulfate hexahydrate and cobalt sulfate hexahydrate are now represented by their chemical formulae (NiSO4.6H2O and CoSO4.7H2O)
ISL	45	Pg 24	4.1 Project Description	Te	Leveraging this characteristic, TMC aims to minimise waste by creating **by-products** instead of generating a substantial waste stream, avoiding the need for large-scale waste or tailings facilities Comment	Consider to use the right term here, I think it is supposed to be co-product	Corrected to “co-products”

					Does TMC produce by-product or co-product? By-product as in 'waste'? Or co-product as in 'valuable metals'?		
ISL	46	Pg 24	Table 6	Te	Look at my comment for Table 3 above	Look at my comment for Table 3 above	This is now Table 5. Correction to the naming of nickel sulfate hexahydrate and cobalt sulfate hexahydrate made. For consistency, Throughout the report nickel sulfate hexahydrate and cobalt sulfate hexahydrate are now represented by their chemical formulae ($NiSO_4.6H_2O$ and $CoSO_4.7H_2O$)
ISL	47	Pg 24	Chapter 4.2.1	Te	The SiMn made from the traditional terrestrial route used for the comparison scenario has the same function as the SiMn created from polymetallic nodules What **supply chain** is this terrestrial route? What ore types and processing technology? Pyro, hydro or pyro-hydro?	Add extra information about the comparison scenario, supply chain terrestrial route	Project 1 has now been removed from the report.
ISL	48	Pg 29	Chapter 4.3.1	Te	Which supply chain is this terrestrial Si-Mn ore mining and processing?	Add extra information about the supply chain of terrestrial route, incl. the ore type	Project 1 has now been removed from the report.
ISL	49	Pg 31 – 32	Chapter 4.3.2 and Chapter 4.4.1	Te	Where is the "**dry polymetallic nodules processed**"? This has been selected as one of the FUs	Provide more information about dry polymetallic nodules Where is this product within the system boundary?	Refer to the response to comment ISL38
ISL	50	Pg 32	Chapter 4.4.2 to Chapter 4.4.2.1	Te	The description of **RKEF process is quite similar to the processing technique of nickel saprolite** ore. Do the nodules from DSM processed together with nickel saprolite ore? If yes, how did you apply the allocation of nickel ore vs nodules?	Add information about the RKEF process, blending with nickel saprolite ore? Especially for the Project 2 when RKEF takes	There is no input of saprolite ore. The metal- containing input in the process are the polymetallic nodules as described in section 4.4.2.1

						place in Indonesia	
ISL	51	Pg 29	Chapter 4.6	Te	The **cut-off criteria is 3% by mass** However, a small quantity of chemical or reagent (<3% by mass) can contribute to more than 5% Climate Change Impact. Is there any reference that we can use to justify the cut-off criteria 3% by mass?	Consider adding a reference and justify the cut-off criteria 3% by mass	This sentence has now been removed completely
ISL	52	Pg 42	5.1 Data Collection and Calculation	Ed	Two Ecoinvent database is used in Project 1 and Project 2. Why? Any impact to the results and LCIA interpretation?	Give a brief explanation why the database used in Project 1 and Project 2 are different and any impact associated with it, if any (e.g., LCIA analysis and interpretation)	Project 1 has now been removed from the report.
ISL	53	Pg 43 and Pg 46	Table 11 and Table 14	Ed	Ni-Cu-Co matte additional notes: "**Fed into the pyrometallurgy (Conversion of MnSi to SiMn) stage**" Is this correct? Ni-Cu-Co matte is fed to hydrometallurgy stage?	Is this typo? Or am I missing something?	Project 1 has now been removed from the report.
ISL	54	Pg 43 and Pg 46	Table 11 and Table 14	Ge	Why is 50% 'Graphite production' and '50% market for carbon black' is selected for Electrode Past LCI?	Any assumption behind this 50:50 split shall be considered to be added and briefly explained in the main text	This is because electrode paste consists of anthracite combined with other carbon based materials to enhance properties. therefore it was modelled as 50-50 graphite and carbon black. The amount of electrode paste consumed annually is very small and thus the impact is negligible. However a sentence on the assumption is now added.
ISL	55	Pg 46	Table 14	Te	The ecoinvent database for Cyanex 272: "market for phosphoric acid, fertiliser grade, without water, in 70% solution state" Why is this database chosen as the proxy chemical for Cyanex 272? Is there any chemical	Cyanex 272 is organophosphorus chemicals, and there is dataset on organophosphorus impact in Ecoinvent that	Phosphoric acid is now replaced with organphosphorous.

					properties or characteristics that is similar to Phosphoric Acid compared to Organophosphorus impact?	can be used as proxy	
ISL	56	Pg 52	6.1. Assumptions: Project 1	Te	In the base-case scenario, the mined polymetallic nodules are transported to Texas, and undergo processing (pyrometallurgy) where **it is assumed** that the electricity grid mix comprises 100% wind energy due to a **power purchase agreement** Comment 100% wind energy will drive the impact much lower compared to mixed renewable and non-renewable energy. Do we have any prove of the PPA from them? If the results of this project is made public, we need to be sure that this is something feasible, as base-case 100% wind energy source. Otherwise, I suggest we shall not mention PPA at all		Project 1 has now been removed from the report.
ISL	57	Pg 54	6.2 Assumptions: Project 2	Te	Cyanex-272 (dialkyl phosphinic acid) (input to input to hydrometallurgy process – specifically during Co solvent extraction) – **Phosphoric acid** used as a proxy. Why is this database chosen as the proxy chemical for Cyanex 272? Is there any chemical properties or characteristics that is similar to Phosphoric Acid compared to Organophosphorus impact?	Cyanex 272 is organophosphorus chemicals, and there is dataset on organophosphorus impact in Ecoinvent that can be used as proxy	Phosphoric acid is now replaced with organphosphorous.
ISL	58	Pg 52	6.1 Assumptions: Project 1	Te	The allocation procedure for Project 2 is described in the Assumption Why is the **allocation in Project 1** not described? There is allocation between MnSiO3/SiMn and Ni-Cu-Co matte, right?		Project 1 has now been removed from the report.
ISL	59			Ge	What did we do with the **Slag** produced in **Project 1 from SiMn pyro**? System expansion? Should there be impact associated with it and reflected in the result section and figures?		Project 1 has now been removed from the report.
ISL	60			Ge	What did we do with the **Slag** produced in **Project 2 from Ni-Cu-Co matter pyro**?		In the system expansion section the following sentences have been included:

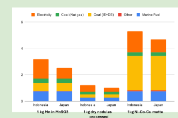
					This is not clear what treatment has been considered for this one System expansion? Should there be impact associated with it and reflected in the result section and figures?		"System expansion (by substitution) was applied to account for ammonium sulfate and converter slag produced during the sulphidisation and conversion stages. Ammonium sulfate was assumed to substitute globally produced ammonium sulfate for the Chemicals and Agriculture industry, while converter slag was assumed to serve as aggregate in road construction." And references to the treatment of ammonium sulfate and converter slap have now been made throughout the report.
JS1	61	1	Title page, Table 1 etc.	ed	**[Minor]** Ensure reviewer changed from Laura Lander to Joris Šimaitis throughout.	Ensure reviewer changed from Laura Lander to Joris Šimaitis throughout.	Corrected to Joris Šimaitis
JS2	62	4 and 23	Executive summary, and Goal of the Study	ed	**[Minor]** *"Unlike terrestrial mining, which requires the removal of overburden and waste rock, polymetallic nodules lie unattached on the seafloor, eliminating the need for extensive land disturbance or waste management."* The statement is potentially subjective and a too firm and not actually been quantified or assessed in this study.	Please add "potentially" somewhere or along those lines.	The following change to the text has been made: "Unlike terrestrial mining, which requires the removal of overburden and waste rock, polymetallic nodules lie unattached on the seafloor, eliminating the need for extensive land disturbance, <u>thus minimising</u> waste management."
JS3	63	5	Executive summary	ed	**[Minor]** *"The primary goal of this LCA is to provide TMC with insights to guide emissions reduction strategies and enhance the sustainability of the metal production process."*	Please specify such as *"to guide environmental impact reduction/mitigation and enhance the*	The following change has been made based on what TMC has specified their goal to be as such:

					The terms are too general and broad, please be more specific. For example, emission reduction does not apply to resource depletion categories.	*environmental sustainability…"*	*"The primary goal of this LCA is to provide TMC with insights to guide environmental impact reduction strategies and enhance the environmental impact profile of the metal production process. The target audience includes investors, customers, and those interested in deep-sea mining."*
JS4	64	8	Executive summary	Ed	**[Minor]** Typo/Formatting CO2 is heading capitalised in the below text. *"In this scenario, the downstream process contributed a larger share of the emissions (6.48 kg* ***CO2*** *eq), as TMC's pre-reduction step, which helps reduce emissions earlier in the production process, was absent"*	Fix formatting error	Formatting error corrected
JS5	65	7	Executive summary	ed	**[Suggestion]** "As shown in Section 7.1, the climate impact per kg of SiMn is 7.04 kg CO2 eq per kg SiMn" You do not need some of the repetition, which will make it easier to read the results. For example, you do not need "per kg SiMn" at the end if you said it at the start.	"kg of SiMn is 7.04 kg CO2 eq per kg" – I recommend trying to change this throughout.	Correction made throughout the report.
JS6	66	23	3. Goal of the Study	Ed	**[Minor]** *"The LCA conducted is an attributional LCA, meaning the global environmental impacts associated with producing the metals are considered. This is based upon the physical flows to and from the life cycle of the product and its subsystems"* I think the definition can be slightly clarified. Please make a few specific references to environmental account, and than marginal/indirect effects such as those used in consequential LCA are not considered – this is	Refine along the lines of… *"The LCA conducted is an attributional LCA. This takes an environmental accounting approach that assigns environmental burdens to products based on existing systems upon the physical*	This is a great suggestion. As you have advised, the text now reads: *"The LCA conducted is an attributional LCA. This takes an environmental accounting approach that assigns environmental burdens to products based on existing systems upon the physical flows to and from the life cycle of the product*

					always a inherent limitation of attributional LCA, and I think should somewhat disclosed.	*flows to and from the life cycle of the product and its subsystems – but does not consider marginal and indirect market effects such as changes in supply and demand"*	*and its subsystems – but does not consider marginal and indirect market effects such as changes in supply and demand."*
JS7	67	24	4. Scope of assessment	Te	[**Major**] For the comparison scenario, I cannot find its actual details or sources in this section, Figure 4, and Table 13, it seems to be missing. In section 8.1 is where the description LCI appears, and I think needs to be removed from the results section, and declared and discussed in the product system sections. I am assuming this is citation [12] which seems to only appears in section 8.1.	Please develop and declare the comparison scenario in the earlier sections of the report, and discuss the source.	Project 1 removed from the report
JS8	68	28	4.3.1. System boundary – project 1	Ge	[**Suggestion**] Silico-manganese and SiMn seem to be used interchangeably, makes it a little more difficult to read.	I recommend just sticking to SiMn throughout this section as I think its previously already been defined?	Project 1 removed from the report
	69	29	Table 7	Ed	[Minor] If the production of MnSiO3 takes place in Texas/Japan/Indonesia, then transportation to China or Malaysia for processing to SiMn could be important, and I don't seem to see why the following omission was justified? "Transport of TMC's MnSiO3 to China or Malaysia for processing to SiMn"	Please justify and elaborate why the transportation step has been omitted in the given case.	Project 1 removed from the report
JS9	70	32	4.4.Product System Boundary Description	Ge	[**Suggestion**] These sections would really benefit from diagrams and illustrations explaining the nodules and several vessels used etc. since it can be difficult to read technically descriptions without visuals.	Not essential to implement here, but worth considering for future projects to help the reader visualise.	Thanks for this suggestion. This will be taken on board in future studies.
JS10	71	38	4.5.1.System expansion	Te	[**Minor**] For both ammonia and slag where system expansion is	Justify and elaborate the use of system	In this section the following sentence

					used, it is not elaborated or justified why, Is ammonia being sold or actually used as a product in another supply-chain? Is the slag also a useful product, or is it waste? If it's waste, it cannot be used for system expansion and needs to be linked to a waste treatment process,	expansion for ammonia and slag.	has been included: "System expansion (by substitution) was applied to account for ammonium sulfate and converter slag produced during the sulphidisation and conversion stages. Ammonium sulfate was assumed to substitute globally produced ammonium sulfate for the Chemicals and Agriculture industry, while converter slag was assumed to serve as aggregate in road construction." And references to the treatment of ammonium sulfate and converter slap have now been made throughout the report.
JS11	72	39	4.5.2/Table 10	Te	**[Minor]** There seems to be no reference to the 10-year price average of materials.	Please include a citation.	Table 10 (which is now Table 8)now features the following footnotes (including references): *The 10-year average prices for the metals are for the years 2014-2023. [43.44] **Economic allocation using a forecasted 10-year average market value, using data sourced from CRU.[45]
JS12	73	42	5.1. Data collection and calculation	Ge	**[Minor]** The foreground system data collection is very general, which is fine, but somewhere and discussing with the client, please disclose a data statement that these technical reports could be accessed if requested and agreed with the client. This is important since this is currently an inaccessible "black box" with no traceability or	Please disclose a data statement that these technical reports could be accessed if requested and agreed with the client.	The 'Data collections and calculation' section now states the following: "Foreground data, relating to offshore operations, pyrometallurgy and hydrometallurgy processes were sourced from TMC's

					replicability in how the LCI was developed. Other details such as characterisation of the nodules and materials contents would be useful.		internal NORI-D project Pre-feasibility study (PFS) (October 2024) and offshore data from SK-1300 compliant NORI Initial Assessment (March 2021).[47]" A reference to the latter is provided.
JS13	74	43	5.2. / Table 11	Ed	[Minor] 332,526 tonnes marine fuel translating to around 1,047,564 tonnes CO2 sounds about right based on potential carbon contents. I am not clear why the CO2 sensitivity tests for India and Malaysia are greater? The CO2 emission don't seem to tested in section 9.1. later on. [Minor] Missing amounts in electrode paste, and missing units for CO and SO2 emissions. [Minor] Ni-Cu-Co matte says it is fed into pyrometallurgical stage in Table 11 later, but I do not see this? It seems pyrometallurgical process feeds only MnSi Rich Slag and not Ni-Cu-Co matte	Please clarify or correct if needed.	Project 1 removed from the report
JS14	75	46	5.3. / Table 14	Te	[Minor] It is not clear why only the marine fuel is included, and direct CO2 emissions are no longer specified as they were in Table 11?	Please clarify.	Marine fuel (IE + DE) are the indirect (production) and direct (combustion) emissions of the fuel.
JS15	76	57	7.1.1. Climate Change by Stage	Ed	[Suggestion] Figures 5 and 6 go straight into a detailed contribution analysis. I think a preceding figure would be beneficial and clearer, providing an overview of the contributions between Offshore mining" vs. "MnSiO3" processing" vs. "SiMn production". For example, I expected to start with a similar figure as in Figures 27 and 28.	Section 7.1. include overview contribution analysis that clearly shows Deepsea mining vs MnSiO3 production vs SiMn production	Project 1 removed from the report
JS16	77	59	7.1.3. Climate Change Scope Emissions	Ed	[Minor] Figure 7 Could you clarify why electricity impacts have not been included under scope 2, because this refers to energy	Please check and clarify.	Project 1 removed from the report

					consumption-based emissions? I'm not sure it's correct?		
JS17	78	61	7.2. Climate Change – Project 2	Ed	[**Suggestion**] Figures 8-13 and descriptions are repetitive, and makes the section hard to follow, or obtain comparable insights between the regions and functional units. Because the charts are the same but only vary in the region and functional unit, you could neatly package this section into a single bar chart, which would be more insightful and comparable and make the section more concise, such as in Figure 44.	You can combine all these charts into one bar chart, you can expand the example below of what I mean. Alternatively, include a few of the original figures and then you can summarise the rest using a table. 	The graphs have been separated based on specific requests from the client. However, a summary graph similar to the one you have shown has been included in the executive summary.

JS18	79	62	7.2.1. / Figures 8-9	Ed	**[Minor]** Figure 8-9 the marine fuel changes from 0.76 to 0.77. I am assuming this is same number but rounding differences.	Ensure you are consistent with the rounding in applicable.	This minor difference is due to the additional distance travelled by the marine vessels from Indonesia to Japan. In reality, the route travelled to Japan comprised a journey to Indonesia + additional miles from Indonesia to Japan.
JS19	80	68	7.2.3. / Figure 13	Ed	**[Minor]** Figure 13 now includes silica on the x-axis which was not in the previous figures – perhaps double check this?	Check if the silica was correctly included	This is because the functional unit is the matte, which has a smaller mass and uses more silica, therefore the impact is greater than 1% of the total and does not fall into the other category.
JS20	81	70	7.2.4.-onwards	Ed	**[Suggestion]** Figures 14-19 have the same issue as in **JS17** and can be combined into one figure. Without a comparative figure, it is for example difficult to see how the various allocation choices lead to each of the products having varying impacts.	Combine figures as in XXX that shows a comparative contribution analysis.	Whilst repetitive this has been done for ease of reading for the client and their audience. However Figure 2 (executive summary) has been added. It presents a side by side comparison of total climate change impacts for each target metallic product, when pyrometallurgy occurs in Japan or Indonesia.
JS21	82	79	7.2.7 / Figures 20-22	Ed	**[Suggestion]** Figures 20-22 can also be combined into one figure.	As in **JS17** ,combine figures which shows the scope1-3 as contributions comparatively between the different products and regions.	Before Figures 20, 21 and 22 featured two graphs side-by-side each. At the request of the client, each pair of graphs have been merged into one, allowing for an Indonesia vs Japan comparison per scope type. These figures are now 17-19.

JS22	83	81	8. Results - Comparison scenarios	Ed	[Suggestion] There is a switch from project 1 to project 2, then back to project 1 in section 8, which is challenging to follow.	Move section 8 into project 1 (7.1.)	Project 1 removed from the report
JS23	84	82	8.1. / Figure 23	Ed	[Minor] Figure 23 uses global warming potential terminology, use climate change instead as used consistently in the other figures. Found in Figure 27 too.	Ensure you use climate change consistency throughout the doc. Ctrl+F for global warming potential.	Project 1 removed from the report
JS24	85	83	8.2. / Figures 23-24	Ed	[Minor] Figure 24 and 25 are good but do not give insight into why these impacts differ.	Break down the bar charts into some contributions, either detailed process stages, or scope 1-3's. Please also discuss more into how and why the impacts differ.	Project 1 removed from the report
JS25	86	86	9.1.1 / Sensitivity Analysis - Project 1	Ed	[Suggestion] "This analysis shows that the LCA model for climate change impact is most sensitive to the climate change impact contribution of the electricity required during the carbothermic reduction of MnSiO3 to SiMn" A bit of repetition, can streamline the writing here slightly, in addition to wherever it else this can apply.	Make the writing a little more concise such as… "This analysis shows that the LCA model for climate change impact is most sensitive to the electricity required during the carbothermic reduction of MnSiO3 to SiMn"	Project 1 removed from the report
JS26	87	109	10. Conclusions and Recommendati ons	Ge	[Suggestion] Under project 1, it may be useful to add a comment in what steps the TMC's SiMn process can take to decarbonise based on the sensitivity analysis etc. [Suggestion] There is some discussion on the limitations of the pilot scale plant, it could be interesting to discuss how a full scale operation would change the results, such as potential economies of scale reductions in energy consumption etc [Major] For project 2, I believe the major uncertainty that has not been discussed in the allocation methods.	If applicable, discuss TMC's decarbonisation more broadly and add discussion surrounding what could happen if full scale production. Please add limitations discussion on the allocation methods, and also revisit section 4.5.2. and page 38 to add evidencing/justif ication why	Project 1 has been removed from this report. A sensitivity analysis on the economic allocation based on a 10-year average forecast price (2025-2036) for Cu, Ni, and Co metals has been added. Previously a 10 year average (2011-2021) price for Ni, Cu, and Co has already been applied. This has been updated to 2014-2023.

					The results drastically would change based on mass for example or different economic-year periods, and this was not tested with sensitivities or justified in section 4.5.2. – see my citation suggestion to next column.	economic allocation is used. Perhaps this may be a useful citation: Santero, N., Hendry, J. Harmonization of LCA methodologies for the metal and mining industry. Int J Life Cycle Assess 21, 1543–1553 (2016). https://doi.org/10.1007/s11367-015-1022-4.	A sensitivity analysis using metal mass based allocation has also been added.

“type of comment”: the type may be referring to “general” (ge), “editorial” (ed) or “technical” (te)

CRITICAL REVIEW STATEMENT

Study Name	LIFE CYCLE ASSESSMENT OF VARIOUS PRODUCT OUTPUTS FROM THE NORI-D POLYMETALLIC NODULES PROJECT - Dated November 8th 2024 - Report version 2.2
Commissioner of LCA Study	**The Metals Company (TMC)**, Headquarters: Vancouver, Canada.
Practitioners of LCA Study	Keno Ignace and Lorraine Amponsah **Minviro Ltd**, Metal Box Factory, Room GG.005, 30 Great Guildford St, London, SE1 0HS
Critical Reviewer(s)	Chair: Quentin Dehaine External Reviewer: Joris Šimaitis Internal Reviewer: Irdanto Saputra Lase

Scope of the Critical Review

The critical review process was conducted in accordance with international life cycle assessment standards, as outlined in *ISO/TS 14071:2014* (Critical Review Processes and Reviewer Competencies).

- The study adhered to the following international standards:
  - *ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework.*
  - *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines.*
- The methods used in the study are scientifically and technically valid.
- The data used are appropriate and reasonable in relation to the goal of the study.
- The report is transparent and consistent with the study's aims.

The critical review covered all aspects of the LCA, including data appropriateness and reasonability, calculation procedures, life cycle inventory, impact assessment methodologies, characterisation factors, calculated life cycle inventory and life cycle inventory analysis results, and interpretation.

Critical Review Process

In November 2024, Quentin Dehaine, Joris Šimaitis, and Irdanto Saputra Lase were engaged by Minviro Ltd, the practitioner of the LCA study titled "*Life cycle assessment of various product outputs from the NORI-D polymetallic nodules project*", to perform an independent expert critical review. The study quantifies climate change, as well as all of the other impact categories available through the EF methodology associated with the production of $MnSiO_3$, Ni-Cu-Co matte, $NiSO_4·6H_2O$, $CoSO_4·7H_2O$ and copper cathode.

The critical review was conducted at the end of the study and included assessments of report versions 1.1 (received October 3rd 2024), version 2.0 (received November 1st 2024), and the final version 2.1 (received November 8th 2024). As part of the review, the life cycle inventory model and the use of foreground and background datasets, as outlined in the reports, were evaluated.

Critical review comments were provided by Quentin Dehaine, Joris Šimaitis, and Irdanto Saputra Lase for report version 1.1 on October 3rd 2024; version 2.0 on November 1st 2024; and version 2.1 on November 8th 2024. No further comments were issued for version 2.2, which is presented here. The critical review comments and responses are included in 'Appendix B – Findings and Recommendations of the Critical Review'.

Study Evaluation

The LCA study has certain strengths, limitations and potential improvements as described in Section 6 of the latest version of the report herein presented. To the best of our knowledge and with the data we have in hand, this study is in conformance with ISO 14040:2006, and ISO 14044:2006. This critical review statement, prepared on November 8th 2024, will be appended to the final LCA report on submission to The Metals Company (TMC).

Conclusions

The critically reviewed LCA study complies with *ISO 14040:2006*, and *ISO 14044:2006*. The report appropriately summarises the study's goals, scope, methodology, assumptions, life cycle inventory, data quality, results, and sensitivity analyses.

Responsible for the critical review report and critical review statement have been the following reviewer(s):

Quentin Dehaine
Senior Researcher
Geological Survey of Finland

08/11/2024

Joris Šimaitis
LCA Consultant,
Life Cycle Solutions

08/11/2024

Irdanto Saputra Lase
Sustainability Scientist
Minviro Ltd

08/11/2024

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

☑ I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study (external reviewers only)

☑ I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s)

☑ I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

☐ ISO 14040 and ISO 14044

☐ LCA methodology and practice, particularly in the context of LCI, (including data set generation and data set review, if applicable)

☑ critical review practice

☑ the scientific disciplines relevant to the important impact categories of the study

☑ environmental, technical and other relevant performance aspects of the product system(s) assessed

☑ language used for the study

I attach a curriculum vitae and a list of relevant references.

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 08/11/2024

Name (print): QUENTIN DEHAINE

Signature:

Quentin **Dehaine**

PhD · MSc · BSc

Iivisniemenkatu 4 F106, 02260 Espoo, Finland

+33(0)677212926 | quentin.dehaine@gmail.com | RG Profile | Google Scholar | qdehaine | @Quentin_Dehaine | quentin.dehaine

Expertise: Traceability, Applied Mineralogy, Battery minerals, Geometallurgy, Mineral Processing, Circular Economy, Theory of Sampling

Education

Université de Lorraine — *Nancy, France*

PhD in Minerals Engineering — *January 2013 - March 2016*

- **Title:** Rare Earths (La, Ce, Nd) and rare metals (Sn, Nb, W) recovery from micaceous waste of china clay production. **Director:** Pr Lev Filippov
- Ph.D. supported by the European FP7 STOICISM project, in partnership with IMERYS Minerals Ltd. **Defended on March 2016**, 6 publications.

Universidade Federal de Minas Gerais (UFMG) — *Belo Horizonte, Brazil*

Exchange Student — *February 2012 - July 2012*

- A 6 months exchange in the IGC (Institute of Geosciences), courses in metallogeny, applied geophysics, and field geology

Ecole Nationale Supérieure de Géologie (ENSG) — *Nancy, France*

Postgraduate student — *September 2009 - September 2012*

- Master of Engineering in Ore Geology and Mining, graduated in September 2012

Work Experience

Independant Technical Expert — *Remote*

Technical Reviewer (Secondary Occupation) — *March 2023 - Present*

- Conducting technical reviews of Life Cycle Assement (LCA) studies for companies and consultancies as part of a reviewer panel or as a chairperson.
- LCA of battery minerals processing and chemicals manufacturing (Lithium, Cobalt, Manganese).

Geological Survey of Finland - Geologian tutkimuskeskus (GTK) — *Espoo, Finland*

Senior Researcher — *January 2021 - Present*

- Conducting research on battery minerals (Lithium, Cobalt, Nickel) geometallurgy and traceability within the circular economy solutions unit.
- Scientific coordinator for the Business Finland (BF) BATTRACE and the Horizon Europe (HE) MaDiTraCe and EXCEED projects.
- Cobalt factsheet for the SCRREEN3 project.
- Writing and coordinating grant applications (ERA-MIN, HORIZON EUROPE, Business Finland).
- Commercial activities, including geometallurgical scoping studies, for battery minerals projects.

Postdoctoral Research Associate — *May 2019 - December 2020*

- Working on geometallurgy of battery minerals (mainly cobalt), through various projects including BATCircle, and GTK-funded projects.

Camborne School of Mines (CSM) - University of Exeter (UoE) — *Penryn, UK*

Postdoctoral Research Associate — *January 2017 - April 2019*

- Working on the NERC project CoG3:"Geology, Geometallurgy & Geomicrobiology of Cobalt". Main focus on improving the cobalt supply chain through investigation into the geometallurgy of cobalt with direct engagement of industry.

Université de Lorraine (UL) — *Nancy, France*

Postdoctoral research fellow — *April 2016 - December 2016*

- Working on the H2020 project FAME:"Flexible and mobile economic processing technologies". Focusing on new processing technologies for low grade complex ores with a focus on greisen (Sn), skarn (W) and pegmatite (Li) deposits across Europe.

EMerald - ENSG - UL — *Nancy, France*

Instructor — *January 2013 - December 2016*

- Instructor for Emerald Master students (European Master program in Georesources Engineering) and for ENSG 3rd year students, teaching mineral processing, material balance, process modelling.

VALE New Caledonia — *Goro Ni-Co project, New Caledonia*

Geologist intern — *July 2011 - January 2012*

- 7 months internship in the mine department working on structural mapping and structural modelling of the exploited area using ArcGis and Datamine based on aerial photo-interpretation, field observations and geophysical data.

Skills

Languages — **English:** Fluent (2011 Cambridge IELTS, B2), **French:** Native speaker, **Portuguese:** Professional working proficiency.

Research — Report writing, Data collection & Processing, Critical thinking, Project & Budget management, Grant writing.

Softwares — MS Office suite, Matlab, JMP (SAS), Bilco, UsimPac, ArcGIS, Adobe Illustrator.

Programming — Python, C/C++, LaTeX.

Awards & Grant Applications

Awards

2018	**Recipient**, Outstanding contribution award in reviewing for Minerals Engineering journal	*Elsevier*
2016	**Winner**, PhD Thesis Award of *Université de Lorraine* for the Earth and Environment 'OTELo' center	*Nancy, France*
2016	**3rd Prize**, PhD Thesis Award of RP2E doctoral school of *Université de Lorraine* (108 candidates)	*Nancy, France*
2014	**1st Place**, SIM PhD Student Award, presented at the 63rd *Société de l'Industrie Minérale* (SIM) congress	*Bordeaux, France*

Grant Applications

2019	**Marie Skłodowska-Curie Actions**, Postdoctoral Fellowship - **Score:** 88.2% - Seal of excellence	*Not funded*
2020	**BATTRACE**, Business Finland Co-Innovation project, Coord.: VTT/GTK, Task Leader	*Funded - 6 M€*
2022	**EXCEED**, Horizon Europe project, Coord.: VTT, WP Leader - **Score:** 15/15	*Funded - 12.3 M€*

Publications (Citations: 776, *h*-index: 14, *i10*: 16)

SELECTED PEER REVIEWED INTERNATIONAL JOURNALS (18 out of 26)

- **Dehaine, Q.**, Filippov, L.O., 2015. Rare earth (La, Ce, Nd) and rare metals (Sn, Nb, W) as by-product of kaolin production, Cornwall: Part1: Selection and characterisation of the valuable stream. *Minerals Engineering* 76, 141–153. 10.1016/j.mineng.2014.10.006
- **Dehaine, Q.**, Filippov, L. (2015). A multivariate approach for process variograms. *TOS Forum* 5, 169 –174. 10.1255/tosf.76
- **Dehaine, Q.**, Filippov, L.O., 2016. Modelling heavy and gangue mineral size recovery curves using the spiral concentration of heavy minerals from kaolin residues. *Powder Technology* 292, 331–341. 10.1016/j.powtec.2016.02.005
- **Dehaine, Q.**, Filippov, L.O., Royer J.J., 2016. Comparing univariate and multivariate approaches for process variograms: A case study. *Chemometrics and Intelligent Laboratory Systems* 152, 107-117. 10.1016/j.chemolab.2016.01.016
- **Dehaine, Q.**, Filippov, L.O., R. Joussemet, 2017. Rare earths (La, Ce, Nd) and rare metals (Sn, Nb, W) as by-products of kaolin production, Cornwall - Part2: Gravity processing of micaceous residues. *Minerals Engineering* 100, 200-210. 10.1016/j.mineng.2016.10.018
- **Dehaine, Q.**, Filippov, L.O., Glass, H.J., Rollinson, G.K., 2019. Rare-metal granites as a potential source of critical metals: a geometallurgical case study. *Ore Geology Reviews* 104, 384-402. 10.1016/j.oregeorev.2018.11.012
- **Dehaine, Q.**, Foucaud, Y., Kroll-Rabotin, J-S., Filippov, L.O., 2019. Experimental investigation into the kinetics of Falcon UF concentration: Implications for fluid dynamic-based modelling. *Separation and Purification Technology*. 10.1016/j.seppur.2019.01.048
- Tijsseling, L., **Dehaine, Q.**, Rollinson, G.K., Glass, H.J., 2019. Flotation of mixed sulphide oxide copper-cobalt minerals using xanthate, dithiophosphate and thiocarbamate collectors. *Minerals Engineering* 138, 246-256. 10.1016/j.mineng.2019.04.022
- **Dehaine, Q.**, Michaux, S.P., Pokki, J., Mari, K., Butcher, A.R., 2020. Battery minerals from Finland: Improving the supply chain for the EU battery industry using a geometallurgical approach. *European Geologist Journal* 49, 5-11. 10.5281/zenodo.3938855
- Tijsseling, L., **Dehaine, Q.**, Rollinson, G.K., Glass, H.J., 2020. Mineralogical Prediction of Flotation Performance for a Sediment-Hosted Copper–Cobalt Sulphide Ore. *Minerals* 10, 474. 10.3390/min10050474
- **Dehaine, Q.**, Tijsseling, L., Glass, H.J., Törmänen, T., Butcher, A.R., 2021. Geometallurgy of Cobalt Ores: a Review. *Minerals Engineering* 160, 106656. 10.1016/j.mineng.2020.106656
- **Dehaine, Q.**, Filippov, L.O., Filippova, I.V., Tijsseling, L., Glass, H.J., 2021. Novel approach for processing complex carbonate-rich copper-cobalt mixed ores via reverse flotation. *Minerals Engineering* 161, 106710. doi: 10.1016/j.mineng.2020.106710
- Pell, R., Tijsseling, L., Goodenough, K., Wall, F., **Dehaine, Q.**, Grant, A., Deak, D., Yan, X., Whattoff, P., 2021. Towards sustainable extraction of technology materials through integrated approaches. *Nature Reviews Earth & Environment* 2 (10), 665-679. 10.1038/s43017-021-00211-6
- **Dehaine, Q.**, 2021. Loosen the TOS stipulations and face the economic consequences. *Spectroscopy Europe* 33 (7), 32-33. 10.1255/sew.2021.a37
- **Dehaine, Q.**, Tijsseling, L., Rollinson, G.K., Glass, H.J., Buxton, M.W.N. 2022. Geometallurgical characterisation with portable FTIR: Application to sediment-hosted Cu-Co ores. *Minerals* 12 (1), 15. 10.3390/min12010015
- **Dehaine, Q.**, Esbensen, K.H. 2022. Multivariate methods for improved geometallurgy sampling. *TOS Forum* 11, 411-417. 10.1255/tosf.167
- Butcher, A.R., **Dehaine, Q.**, Menzies, A.H., Michaux, S.P., 2023. Characterisation of ore properties for geometallurgy. *Elements* 19, 352-358. 10.2138/gselements.19.6.352
- **Dehaine, Q.**, Tijsseling, L.T., Rollinson, G.K., Glass, H.J., 2024. Flotation of a copper-cobalt sulphide ore: Quantitative insights into the role of mineralogy. *Minerals Engineering* 218, 108958. 10.1016/j.mineng.2024.108958

PEER REVIEWED NATIONAL JOURNALS & MAGAZINES

- **Dehaine, Q.**, 2015. Métaux critiques (terres rares légères, niobium, tungstène) et étain comme coproduits de la production de kaolin. *Mines & Carrières*, hors série 16 (225), 99-111 (in French).
- Duhamel-Achin, I., Bodin, J., **Dehaine, Q.**, 2022. Géométallurgie: De la genèse du gisement à une exploitation optimisée. *Géosciences*, hors série 16 (225), 99-111 (in French). < hal-03767242 >
- **Dehaine, Q.**, 2022. Traiter les particules fines grâce aux séparateurs gravimétriques centrifuges. *Mines & Carrières*, (304), 56-61 (in French).

REPORTS, WHITE PAPERS & OPEN FILES (3 out of 5)

- **Dehaine, Q.**, Farajewicz, M., Michaux, S.P., Butcher, A.R., Cook, N., 2021. Geometallurgical characterisation of the Rajapalot Au-Co project. *Research Report 5/2021*. (Open Access).
- **Dehaine, Q.**, Michaux, S.P., Butcher, A.R., 2021. Metallurgical testwork for the geometallurgical orientation study of the Mawson Gold's Rajapalot Au-Co project. *Research Report 14/2021*. (Open Access).
- Kaikkonen, H., Kivinen, M., **Dehaine, Q.**, Pokki, J., Eerola, T., Bertelli, M., Friedrichs, P., 2022. Traceability methods for cobalt, lithium, and graphite production in battery supply chains. *GTK Open File Research 20/2022*. (Open Access).

Scientific Merits & Societal Impact of Research

INVITED PRESENTATIONS, TALKS AND SHORT-COURSES (10 OUT OF 13)

- **Dehaine, Q.**, 2015. Métaux critiques comme coproduits de la production de kaolin. *Invited talk and award ceremony* at the 63rd *Société de l'Industrie Minérale* (SIM) congress, Bordeaux, France.
- **Dehaine, Q.**, 2018. Smart cobalt recovery as by-product of copper extraction. *Invited talk* at the IOM3 Geometallurgy conference. London, UK.
- **Dehaine, Q.**, 2019. Geometallurgy of cobalt. *Short Course* for the European Lithium Institute (eLi) short courses on "Exploration and processing of battery metals (Li, Co, Ni) primary and secondary resources". Nancy, France.
- **Dehaine, Q.**, 2020. A global geometallurgical assessment of cobalt mining & processing. *Short Course* for the LTU M7008K Geometallurgy course: Geometallurgy in the Nordic Context (Sweden and Finland). Luleå, Sweden.
- **Dehaine, Q.**, 2021. Sustainable & responsible production of battery raw materials. *Invited Talk* for the Geological Society of Finland. Online.
- **Dehaine, Q.**, 2021. Geo-based traceability of battery raw materials. *Invited Talk* at the Data and Traceability in Battery Value Chain Think Tank" of the Circular Design Network project. Online.
- **Dehaine, Q.**, 2022. Cobalt Mining in Finland. *Keynote* at the Oulu Mining Summit. online.
- Butcher, A., **Dehaine, Q.**, Szentpeteri, K., 2023. Analytical methods in geology. *Short Course* for the FEM 2023 conference, Levi, Finland.
- **Dehaine, Q.**, 2023. From rocks to batteries: insights into cobalt mining, mineralogy, and sustainability. *Invited Talk* at SEG conference. London, UK.
- **Dehaine, Q.**, 2024. Trends in cobalt mining and processing in relation to mineralogy. *Keynote* at Process Minerology. Cape Town, South Africa.

ORGANISATION OF INTERNATIONAL CONFERENCES

- **NAMES'16** - *New Achievements in Materials and Environmental Sciences* international conference (5th Edition). November 7-9 2016, Nancy, France. Organising committee member.
- **WCSB12** - *World Sampling Conference on Sampling and Blending*. June 23-25 2026, Cornwall, UK. Organising committee member.

SCIENCE OUTREACH

- **Interview**, Video for the *Eurêka portal for postsecondary education, research and innovation in Lorraine* and the *Factuel magazine* (2016). Presentation of the STEVAL pilot plant and the STOICISM FP7 EU project (in French).
- **Interview**, *DerStandard* (2019). Discussion on cobalt sourcing - *Haben Blutmineralien im Elektroauto bald ausgedient?* (in German).
- **Interview**, *Materia* (3), 68-69 (2020). Presentation of the BATTRACE project - *BATTRACE – Akkumineraalien jäljillä* (in Finnish).
- **Interview**, *L'usine Nouvelle* (2024). Discussion on lithium and cobalt traceability - *Article* (in French).

Miscellaneous

Committees — **Officer for Scandinavia** of the IUGS-IFG (International Union of Geological Sciences - Initiative on Forensic Geology).
Scientific committe member for the PEPR Sous-Sol project piloted by the CNRS and BRGM.

Peer review — Reviewer for *Minerals Engineering*, *Powder Technology*, *Minerals*, *Colloids and Surfaces A*, *Journal of Metallurgical Engineering* and *Separation Science & Technology*.

Editorship — **Guest Editor** for the journal *Minerals* for the special issue Advances in the Geometallurgy of Battery Minerals.
Editorial Board Member for the Springer Nature journal Discover Minerals.

SoMe — Managing the BATTRACE project twitter (@BATTRACE) & LinkedIn accounts.

Referees

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RIO TINTO PROFESSOR OF MINING AND MINERALS ENGINEERING
Previous supervisor - Postdoc referent at University of Exeter, Penryn, Cornwall, UK
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Pr Alan R. Butcher — *Geological Survey of Finland (GTK)*
RESEARCH PROFESSOR OF GEOMATERIALS & APPLIED MINERALOGY
Former postdoc referent at GTK, Espoo, Finland
alan.butcher@gtk.fi | (+358) 295032240

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

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☑ I do not have vested financial, political or other interests in the outcome of the study.

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

☑ ISO 14040 and ISO 14044.

☑ LCA methodology and practice, particularly in the context of LCI, (including data set generation and data set review, if applicable).

☑ critical review practice.

☑ the scientific disciplines relevant to the important impact categories of the study.

☑ environmental, technical and other relevant performance aspects of the product system(s) assessed.

☑ language used for the study.

I attach a curriculum vitae and a list of relevant references.

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 08/11/2024

Name (print): Joris Simaitis

Signature:

Joris Simaitis

JORIS ŠIMAITIS

Life cycle assessment and sustainability practitioner, PIEMA REnvP

31 Shaws Way, Bath, BA2 1QQ | js3700@bath.ac.uk | +44 7960 885788

EDUCATION

MRes+PhD Advanced Automotive Propulsion | University of Bath **Bath, UK | Sep 2020 – Dec 2024**

Thesis title "Future environmental impacts of transport and energy technologies: Prospective life cycle assessment using climate mitigation pathways from integrated assessment models".

MSc Engineering for International Development | University College London **London, UK | Sep 2019 – Sep 2020**

Distinction (86%), dissertation title "Life cycle assessment of biofertiliser from novel digestate treatment value-chains".

MSci Chemistry (International Programme) | University College London **Remote, UK | Sep 2021 – Present**

First-class honours (74%), dissertation title "Activating the edge of graphene: novel access to edge-carboxylated graphene nanoflakes and activating the edge-anhydride for chemical functionalisation and heavy-metal extraction".

WORK EXPERIENCE

LCA Consultant | Life Cycle Solutions (Freelance) **Remote, UK | Sep 2021 – Present**

- Providing consultancy and advisory services in delivering ISO-compliant product LCA, critical review, and methodology development.
- Delivered 11 client LCA projects and critical reviews for lithium-ion batteries, consumer goods, clothing, and construction sectors.
- Advisory services have included providing market trends in LCA, software feedback and development, and start-up advisory.

Policy Secondee | UK Climate Change Committee **London, UK | Feb 2024 – Apr 2024**

- Contributed to delivering the UK's Seventh Carbon Budget, focusing on decarbonizing infrastructure, industry, and waste sectors.
- Technology review of decarbonization options, developing sector datasets, and techno-economic analysis of recycling infrastructure.
- Stakeholder engagement and workshops with UK industry trade associations to review modelling assumptions and preliminary results.

Policy Research Lead | University of Bath **Bath, UK | Jan 2023 – Jul 2023**

- Investigated industry and policy impacts of the first UK local authority (B&NES) to implement net-zero construction policy.
- Stakeholder engagement through workshops and surveys to understand policy reception and acceptance.
- Published report with policymaker recommendations on key challenges for compliance and suggestions for policy improvements.

Founder & Managing Director | Editors for Impact CIC **Remote, UK | May 2020 – Dec 2023**

- Created a UK-based non-profit organization providing free access to content creation and impact representation for charities.
- Managed and mentored a team of 10+ across business development, operations, partnerships, and marketing.
- Impact: 200+ creative volunteers, 100+ projects delivered across 100+ partner charities, and +300,000 estimated beneficiaries.

LCA Analyst | Project NOMAD, EU Horizon 2020 **London, UK | Apr 2020 – Sep 2020**

- Conducted LCA on biofertilizer products for €5.5 million Horizon 2020 funded EU project in circular bioeconomy technology.
- Delivery of final recommendations to a 50+ consortium to pivot the project towards mitigating unintended potential NO_x emissions.

SKILLS

Sustainability: Life cycle assessment (LCA), organisational carbon footprinting, and critical review specialist. Knowhow with delivering ISO 14040 / 14044 / 14064 / 14067 / 14071 standards, PAS 2050, PEF, GHG Protocol, IPCC, and related standards. Familiarity with other sustainability standards such as SBTi's, CDP, TCFD, GRI, B Corp Certification etc.

Software: Python, Brightway2, OpenLCA, SimaPro, GaBi, and Microsoft Office.

Communications: Specialist in scientific and communications in reporting, stakeholder engagement, workshops, and public speaking.

TRAINING

IEMA Certified Carbon Management | GEP Environmental **Remote, UK | Sep 2023**

Organisational carbon footprint methods, reporting, and management strategies to driving sustainability in organizations.

Open Life Cycle Inventory Data manipulation | Départ de Sentier **Grosshöchstetten, CH | Oct 2022**

Training in interpreting, modifying, and forecasting life cycle inventory datasets using the Brightway LCA framework.

Complete Python Bootcamp | UDEMY **Remote, UK | Dec 2021**

Comprehensive guide to Python programming, covering basics, advanced topics, and real-world applications.

End of Life Pathways for EV Batteries | HSSMI **Remote, UK | Nov 2021**

End-of-life strategies for EV batteries, including recycling, repurposing, relevant legislation, and decision-making frameworks.

Lithium-Ion Battery Pack Fundamentals | SMMT Industry Forum **Remote, UK | Nov 2021**

Exploring the design, components, performance, and lifecycle management of lithium-ion battery packs.

ADDITIONAL CONTRIBUTIONS

Feedback to EU batteries carbon footprint methodology | European Commission **Remote, UK | Apr 2024**

Reviewed LCA methods to recommend guidelines, examples, and data procedures to enhance policy effectiveness.

Invited Lecturer | Institution of Engineering and Technology **Bath, UK | Nov 2022**

Delivered 60-minute lecture on electric vehicle sustainability, attracting 150+ attendees covering environmental and LCA insights.

MEMBERSHIPS

Practitioner Member (PIEMA) | Institute of Environmental Management and Assessment (IEMA) **Remote, UK | May 2023 – Present**
Proven competence in environmental management, sustainability practices, and leading organizational sustainability initiatives.

Registered Environmental Practitioner (REnvP) | Society for the Environment (SocEnv) **Remote, UK | May 2023 – Present**
Demonstrated expertise in environmental management, sustainable practices, and driving sustainability initiatives within organizations.

CONFERENCES

Long talk | **SETAC Europe 26th LCA Symposium** **Gothenburg, SE | Oct 2024**
"How Do Future Scenarios Impact Environmental Outcomes? Prospective Life Cycle Assessment Of Passenger Car"

Long talk | **Future Propulsion Conference** **Solihull, UK | Feb 2024**
"Net Zero Futures in Life Cycle Assessment of Passenger Cars"

Long talk | **11th International Conference on Industrial Ecology** **Leiden, NL | Jul 2023**
"Future environmental impacts of passenger vehicles: Time-adjusted prospective life cycle assessment methods"

PUBLICATIONS

Šimaitis J, Lupton R, Vagg C, Butnar I, Sacchi R, Allen S, Future carbon footprints of passenger cars. 2024. *Submitted manuscript*

Šimaitis J, Butnar I, Sacchi R, Allen S, Lupton R, Vagg C. Expanding scenario diversity in prospective LCA and exploring the life cycle impacts of decarbonising global electricity: coupling the TIAM-UCL integrated assessment model with Premise and Ecoinvent. 2024. *Submitted manuscript*

Šimaitis J, Allen S, Vagg C. Are future recycling benefits misleading? Prospective life cycle assessment of lithium-ion batteries. Journal of Industrial Ecology. 2023. https://doi.org/10.1111/jiec.13413.

Simaitis J, Hawkins W, Shea A, Allen S, Marsh E, Phelps P, et al. Pioneering Net Zero Carbon Construction Policy in Bath & North East Somerset: Investigating the industry's response to the introduction of novel planning policies. 2023. https://doi.org/10.15125/BATHRO-297388880.

Elmagdoub A, **Šimaitis J,** Halmearo M, Carlson U, Turner J, Brace C, Akehurst S, & Zhang N. Freevalve: A Comparative GWP Life Cycle Assessment of E-fuel Fully Variable Valvetrain-equipped Hybrid Electric Vehicles and Battery Electric Vehicles. SAE Technical Paper Series. 2023. https://doi.org/10.4271/2023-01-0555

Lamb J, **Šimaitis J**, Halukeerthi S, Salzmann C, & Holland, J. Graphene Nanoflake Antibody Conjugates for Multimodal Imaging of Tumors. *Advanced NanoBiomed Research.* 2021. https://doi.org/10.1002/anbr.202100009

VOLUNTARY ROLES

Engineering & Environment Mentor| Cable **Remote, UK | Jun 2021 – Sep 2021**
Provided guidance and support to 5 students fostering skills in sustainability and engineering practices.

From Linear to Circular Alumni | Ellen MacArthur Foundation **Remote, UK | Apr 2021 – Jul 2021**
Selected from 1,300+ applicants for a circular economy program to lead Garçon Wines' reusable packaging supply chain project.

Contributing Writer | Degrees of Change **Remote, UK | Jun 2020 – Mar 2021**
Research and communication on circular economy with 100+ reads: "Mobilizing the Circular Economy" and "Theory to Action."

Workshops Officer | Engineers Without Border-UCL **London, UK | Sep 2018 – May 2020**
Managed team of 5 to deliver 6 sustainability workshops to 85+ UCL students; co-founded award-winning "Designathon" event.

English Teacher | Come on out-Japan **Tokyo, JP | Jul 2019 – Aug 2019**
Taught 20+ Japanese high school students in a national program, enhancing their leadership, communication, and public speaking skills.

Events Officer | UCL Green Economy Society **London, UK | Oct 2018 – Apr 2019**
Organized and managed sustainability-focused events and initiatives

Renewable Energy Development Engineer | EcoSwell **Lobitos, PE | Jul 2018 – Aug 2018**
Collaborated with interdisciplinary team on sustainable projects for rural communities, leading data analysis and delivering a solar distiller.

AWARDS & ACHIEVEMENTS

Finalist | 3 Minute Thesis Bath **Bath, UK | Jul 2023**
Selected finalist showcasing the ability to effectively communicate complex research to a broad audience.

Best Academic Society | University College London **London, UK | May 2020**
Awarded for Engineers Without Borders UCL, recognizing outstanding contributions to sustainability and engineering-focused initiatives.

International Challenge Winners | Efficiency for Access Design Challenge **London, UK | May 2020**
Project Lead of UCL team for the Efficiency for Access Design Challenge, focusing on off-grid cooking solutions for emerging markets.

Poole Prize | Department of Chemistry, University College London **London, UK | Jun 2017**
Awarded for the most distinguished work in Physical Chemistry at UCL.

PERSONAL INTERESTS

Interests: Psychology, Mindfulness, and Philosophy.
Languages: Native in Lithuanian and English, learning French.
Sports: Triathlon, Hiking, Rowing, Tennis, Weightlifting.

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Date: 8th November 2024

Name (print): Irdanto Saputra Lase

Signature:

Irdanto Saputra Lase, PhD

✉ irdantosaputra.lase@gmail.com +44 7462 525001

I have a background in Geology, Natural Resources Management, Project Management, Circular Economy and Sustainability Assessment. Currently, I am working as a Sustainability Scientist at Minviro's R&D Department, focusing on responsible critical raw material supply chains, renewable energy, and decarbonization technologies. At Minviro, I lead research on sustainable polymers, Li-ion battery circularity (NMC, LFP, NCA, LCO), battery recycling (pyrometallurgy, hydrometallurgy, and direct recycling) and carbon capture storage and utilization (CCUS), particularly the mineral carbonation technique. I completed my doctoral studies at Ghent University and Maastricht University. My key doctoral research areas are sustainability and circular economy implementation of plastic, including research around advanced chemical recycling (pyrolysis, gasification, and solvent-based recycling) of plastic waste, also as an alternative feedstock in the petrochemical industry. I have been using several tools such as material flow analysis (MFA), techno-economic assessment (TEA), life cycle assessment (LCA), and socio-economic assessment (LCC and SLCA) to perform sustainability and circular economy assessment as well as business development of new emerging recycling technologies. I have experience to work in collaboration with multiple European stakeholders, incl. the Joint Research Centre (JRC) European Commission, CEFLEX consortium, PerfectSorting consortium, PlastiCity projects, and many more.

EDUCATIONAL BACKGROUND

2020 – 2023 Ghent University and Maastricht University
Doctor of Bioscience Engineering and Doctor of Philosophy
Doctoral thesis: “Modeling material flows through plastic recycling chains”

2018 – 2020 Ghent University, Uppsala University, and TU Bergakademie Freiberg
Master of Science in Sustainable and Innovative Natural Resources Management
Thesis: “Model for steady European state of recycled content in EEE products.”

2012 – 2016 Universitas Padjadjaran
Bachelor of Geological Engineering

WORKING EXPERIENCE

October 2024 - Present
Senior Sustainability Scientist, Minviro Ltd – United Kingdom
- Lead and support commercial projects in raw materials (mining) and energy transition sectors, from finding an LCA and sustainability project to proposal writing and submitting deliverables within the agreed timeline
- Lead and support research grants, from grant application and proposal writing to completing the tasks and deliverables
- Lead and support internal research initiatives at Minviro

July 2023 – September 2024
Sustainability Scientist, Minviro Ltd – United Kingdom
- Life cycle assessment of critical raw materials supply chain (Nickel, Lithium, Cobalt, etc.) following ISO 14040/44 standards, incl. ISO 14067, GHG Protocol
- Leading scientist on research projects (grants) on sustainable Lithium-ion battery (NMC, LFP, LCO) recycling and semiconductor manufacturing.
- Life cycle costing (LCC) and Circular Economy Evaluation following ISO 15686 and ISO 5900 series of raw materials supply chain.
- Leading research on sustainable polymer, circularity of Li-ion battery, carbon capture utilisation and storage (CCUS), and policy research in Europe and the UK.
- Leading environmental certification following ISO 14000 and ISO 17000 families
- Supporting commercial teams in business development with science-based evidence

July 2020 – August 2023	***Researcher,* Ghent University & Maastricht University - Belgium and Netherlands** • Techno-economic assessment and business development of advanced flexible packaging waste recycling plants in Europe together with CEFLEX stakeholders • Business development of commercial and industrial (C&I) plastic waste treatment in Western Europe and the United Kingdom within PlastiCity Project framework • Development of 'smart' plastic packaging sorting using artificial intelligence (AI) decision model under PerfectSorting project • Evaluation of recycled content targets in new flexible packaging using mechanical and chemical recycling with CEFLEX stakeholders • Life cycle assessment (LCA) of flexible packaging waste recycling using mechanical and solvent-based recycling options • Evaluation of plastic recycling and recycled content availability from electronic waste (WEEE) in Belgium and The Netherlands, following WEEE and RoHS Directive.
April 2022 – September 2022	***Visiting Scientist,* Joint Research Centre European Commission – Spain** • Assessing the contribution of emerging plastic recycling technologies (chemical recycling and solvent-based recycling) to improve circularity of plastic in Europe • Building an operational framework to quantify 'quality of recycling' of waste treatment • Environmental impact assessment of plastic waste recycling using chemical and solvent-based recycling techniques in Europe
August 2019 – September 2019	***Internship Trainee,* Jan De Nul Group – Taiwan** • Offshore wind farm sustainability and business development review in Asia – Pacific & Europe Region. • Offshore operation training – scour protection installation, project management, and multibeam survey on Grand Canyon II Vessel
March 2017 – June 2018	***Site Engineer,* GeoHarbor Group – Indonesia** • Lead construction site survey and monitoring at Jawa 7 Power Plant Project in Cilegon – Indonesia. Performed daily monitoring of vacuum pre-loading technique. • Lead soil investigation using cone penetration test (CPT) survey and soil profiling at Pemalang – Batang Toll Road Project. Managing soil treatment operation of 32Km-highway project from preparation, project execution, and post-treatment soil monitoring and survey
August 2016 – February 2017	***Junior Geologist,* Patra Nusa Data Elnusa Group – Indonesia** • Worked as a geologist in cooperation with software development and marketing team to advise integrating oil and gas exploration data management in Indonesia. • I made subsurface geological mapping and regional 3D modeling of various sedimentary basins in Indonesia.

PERSONAL SKILLS

Native Language	Bahasa Indonesia
Other Language(s)	English : Fluent Dutch : A.2 level
Software	Microsoft Offices, SimaPro, OpenLCA, MATLAB, eSankey, Ecoinvent.

KEY PUBLICATIONS

Circular economy shaping the future of Lithium-ion batteries. Minviro Whitepaper. 2024.

How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling. Journal Resources, Conservation & Recycling. 2023.

Method to develop potential business cases of plastic recycling from urban areas: A case study on nonhousehold end-use plastic film waste in Belgium. ACS Sustainable Chemistry and Engineering. 2023.

Towards a better definition and calculation of recycling. Publication Office of the European Union.

An operational framework to quantify 'quality of recycling' across different material types. Journal Environmental Science & Technology. Journal Environmental Science & Technology. 2023.

Material flow analysis and recycling performance of an improved mechanical recycling process for post-consumer flexible plastics. Journal Waste Management. 2022.

Quality evaluation and economic assessment of an improved mechanical recycling process for post-consumer flexible plastics. Journal Waste Management. 2022

Expanding the collection portfolio of plastic packaging: impact on quantity and quality of sorted plastic waste fraction. Journal Resources, Conservation & Recycling. 2021.

Multivariate input-output and material flow analysis of current and future plastic recycling rates from waste electrical and electronic equipment: the case of small household appliances. Journal Resources, Conservation and Recycling. 2021.

REFERENCES

Prof. Steven De Meester (Ghent University)	steven.demeester@ugent.be
Prof. Kim Ragaert (Maastricht University)	k.ragaert@maastrichtuniversity.nl
Dr. Davide Tonini (JRC European Commission)	davide.tonini@ec.europa.eu