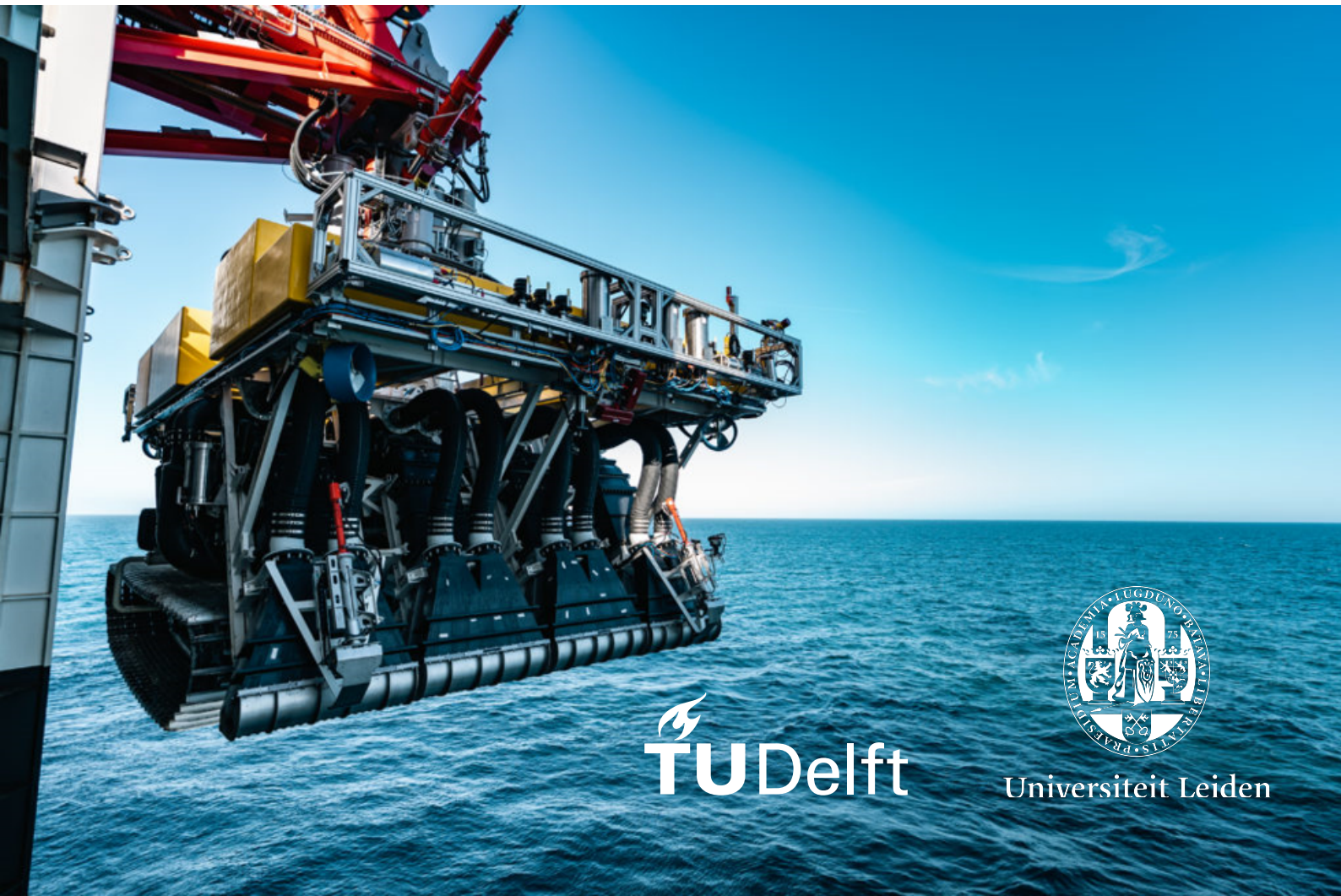


# Comparison of the Environmental Impacts of Metals from Deep-Sea Mined Polymetallic Nodules and Land-Based Mining with LCA

MSc. Industrial Ecology Thesis 2024/2025

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by

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In partial fulfilment of the Master's programme in Industrial Ecology

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# Preface

This thesis research project presents the final phase of my journey toward completing the Master of Science (MSc) in Industrial Ecology. I really enjoyed this interdisciplinary and future-oriented Master's programme. I developed new analytical skills, learned the basics of our Earth system, improved my modelling skills, and developed a more critical and systems-oriented way of thinking. Being surrounded by passionate people who share values similar to mine has also been incredibly motivating. With a strong interest in technology and an even greater passion for environmental sustainability, I am grateful for the opportunity to carry out this thesis research project.

The project was challenging, but provided me with new knowledge and experiences. It allowed me to apply what I had learned in Industrial Ecology, particularly from the LCA course, in a practical context. At the same time, I gained an understanding of the complex field of deep-sea mining, a topic that I had little prior knowledge about. I learned about its technologies and broader context, including regulations, geopolitical tensions, and environmental considerations. The project also strengthened my skills in conducting proper research, leading a project, and thinking critically.

I would like to thank my supervisors, René Kleijn and Rudy Helmons, for their guidance, feedback, and support throughout this research. René provided extensive help with the LCA methodology, shared his expertise in critical raw materials, energy, and mining, and offered guidance on conducting research effectively. Rudy was also highly supportive, sharing his extensive technological knowledge on deep-sea mining and arranging opportunities for me to attend a variety of lectures on the topic. René and Rudy pushed me to get the best out of myself and achieve the full potential of this project. I feel very fortunate to have been supervised by such knowledgeable and dedicated experts.

Finally, I would like to thank my family and friends for their support and involvement throughout this challenging period. Sharing experiences with fellow students who were also working on their thesis made a big difference. I particularly enjoyed the Wijnhaven study sessions with my fellow IE students, as well as the TB and UB sessions with other Delft students. Ralf, Nelene, and Milan also gave me new motivation during our productive and relaxing "thesis get-away" weekend. Furthermore, I am especially thankful to my family for their patience, encouragement, and for always being there to listen. Special thanks to Gijs, Robin, and Lorette for the final checks of my thesis report.

*Floor Broekman  
Delft, August 2025*

# Summary

The urgency of the energy transition, combined with geopolitical tensions over critical raw materials, has increased interest in deep-sea mining of polymetallic nodules. Deep-sea mining is often promoted as a promising alternative to land-based mining, but there are serious concerns about its potential environmental impacts, particularly on biodiversity and ecosystems. Life Cycle Assessment (LCA), a widely used method to assess environmental impacts across a product's life cycle, is currently used to support claims that metals from deep-sea mining are environmentally more preferable than those from land-based mining. However, LCA addresses only generic environmental impacts and previous LCAs comparing deep-sea and land-based mining show considerable variation in outcomes.

This study examined how LCA can be used to inform (policy) decisions about the environmental impacts of metals mined from deep-sea polymetallic nodules compared to land-based mining. The research combined a comparative analysis of previous LCA studies, the development of an aligned LCA, and a critical discussion of limitations. It is important to acknowledge that this study placed greater emphasis on generic environmental impacts, such as climate change, as this aligns with what LCA can adequately assess, while recognizing that biodiversity-related impacts fall outside of this scope.

The comparative analysis showed that all previous LCAs reported lower climate change impacts for deep-sea than land-based mining, but the magnitude of this benefit varied. This was due to methodological choices and assumptions, particularly regarding energy. LCAs with greater benefits for deep-sea mining assumed lower energy use and 100% renewable electricity for nodule processing, while they assumed fossil fuel-dominated mixes for land-based mining. The other LCAs assumed higher energy use and electricity mixes with fossil fuels for deep-sea mining, reducing its perceived advantage. The LCAs with greater benefits for deep-sea mining were supported by a mining company (TMC) with a sponsoring state that advocates deep-sea mining (Nauru), while the others were supported by organisations (GSR & BGR) whose sponsoring states take a middle-ground position (Belgium & Germany).

The aligned LCA integrated data from previous LCAs with recent developments in deep-sea mining. In the baseline model, deep-sea mining outperformed land-based mining in nearly all 20 evaluated categories, except transformation of natural land, including the seabed. The lower impacts of deep-sea mining depended on model choices, particularly regarding energy. Carbon-intensive electricity sources increased the impacts on climate change and energy resources, whereas renewable sources reduced them. This effect was stronger for land-based mining due to its larger contribution from energy processes and higher energy use due to lower ore grades. Under renewable electricity scenarios, land-based mining outperformed deep-sea mining. Other impacts also varied by energy source: hydropower drove high water use, while nuclear energy caused significant ionising radiation, illustrating trade-offs.

This study highlighted the strengths and limitations of LCA in this context. LCA results depend on model choices, data input, and assumptions, and are limited to generic environmental impacts. The method is not suitable to assess location-specific impacts. Nevertheless, these impacts cannot be overlooked, as existing research has shown that deep-sea mining could lead to serious and potentially irreversible impacts on biodiversity and ecosystems.

In conclusion, this study provided valuable insights for policy and decision makers comparing the environmental impacts of metals from deep-sea polymetallic nodules and land-based ores. The reliability of LCA depends on transparency and consistency, yet most deep-sea mining LCAs are industry-supported and lack full transparency. Since LCA does not capture social, economic, biodiversity, and ecosystem impacts, it should be complemented by location-specific assessments and integrated into decision making. Policy makers should also consider other alternatives to land-based mining. This study did not conclude whether deep-sea mining is environmentally more preferable, but it identified conditions under which it results in lower generic environmental impacts than land-based mining, and highlighted critical considerations, knowledge gaps, and uncertainties to guide policy making and future research.

**Keywords:** Deep-Sea Mining, Polymetallic Nodules, Life Cycle Assessment, Energy Transition

# Abbreviations

<b>BGR</b>	German Institute of Geosciences and Natural Resources
<b>CCZ</b>	Clarion Clipperton Zone
<b>CRC</b>	Cobalt-Rich Crust
<b>CRM</b>	Critical Raw Materials
<b>DEME</b>	Dredging, Environmental and Marine Engineering NV
<b>DRC</b>	Democratic Republic of Congo
<b>DSHMRA</b>	Deep-Seabed Hard Mineral Resources Act
<b>DSM</b>	Deep-Seabed Mining
<b>ECS</b>	Extended Continental Shelf
<b>EEZ</b>	Exclusive Economic Zone
<b>EF</b>	Environmental Footprint
<b>EV</b>	Electric Vehicle
<b>GSR</b>	Global Sea Mineral Resources
<b>GWP</b>	Global Warming Potential
<b>IOM</b>	Interoceanmetal Joint Organisation
<b>ISA</b>	International Seabed Authority
<b>JORC</b>	Joint Ore Reserves Committee
<b>JPI Oceans</b>	Joint Programming Initiative Healthy and Productive Seas and Oceans
<b>LCA</b>	Life Cycle Assessment
<b>LCI</b>	Life Cycle Inventory
<b>LCSA</b>	Life Cycle Sustainability Analysis
<b>NORI</b>	Nauru Ocean Resources Incorporated
<b>PAMCO</b>	Pacific Metals Company
<b>PDF</b>	Potentially Disappeared Fraction of species
<b>POF</b>	Photochemical Oxidant Formation
<b>PSV</b>	Production Support Vessel
<b>REE</b>	Rare Earth Elements
<b>RRP</b>	Rules, Regulations, and Procedures
<b>SMS</b>	Seafloor Massive Sulphides
<b>TMC</b>	The Metals Company
<b>UNCLOS</b>	United Nations Convention on the Law of the Sea
<b>USA</b>	United States of America

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# Introduction

The urgency of the energy transition is resulting in an increasing demand for critical raw materials, such as nickel, cobalt, and copper (IEA, 2025b). Up until the mid-2010s, the energy sector accounted for a minor share of the total mineral demand (IEA, 2021b). However, as stated by IEA (2025b), energy applications such as electricity networks, energy storage, and electric vehicles are currently driving the growing demand for critical minerals. In all future scenarios of IEA (2025b), the demand for these materials continues to grow rapidly due to the clean energy sector. In a scenario that follows the stated policies, the demand for copper and cobalt will grow by 30% and 50-60%, respectively, by 2040 (IEA, 2025b). In addition, the nickel demand will double between 2025 and 2040 (IEA, 2025b).

A significant gap between prospective mineral supply and demand is expected, specifically for copper and lithium (IEA, 2025b). Although planned mining and refining projects will increase supply, these projects fall short on copper and lithium, and project delays could complicate the expected increase in supply (IEA, 2025b). Moreover, the realisation of the energy transition depends on the critical raw materials (CRMs) from a limited number of resource-rich countries (IEA, 2025b). Concerns have arisen about the availability of these materials and the security of supply (European Commission, 2025). Every government aims to secure its own energy supply, resulting in competition for CRMs (TNO, 2023). For instance, the USA and Ukraine recently signed a deal that gives the USA access to Ukrainian natural resources (BBC, 2025). In addition, land-based mining is considered a threat to the health of local residents and their quality of life (Mononen et al., 2022). Furthermore, the mining industry has one of the highest accident rates of all sectors and is considered one of the most hazardous sectors (Baraza et al., 2023).

Deep-sea mining is often proposed as a solution (Impossible Metals, 2025b; Loke marine minerals, n.d.; The Metals Company, 2024c). Deep-sea mining is the extraction of ore deposits in the deep sea (MIDAS, 2017a). Three types of deposits that are interesting for deep-sea mining in international waters are polymetallic nodules, seafloor massive sulphides (SMS), and cobalt-rich crusts (CRCs) (MIDAS, 2017a). These deposit types have different characterizations, as presented in Table 1.1.

**Table 1.1:** Three types of deep-sea mineral deposits in international waters, adapted from MIDAS (2017a) and Cherkashov (2022).

	<b>Polymetallic Nodules</b>	<b>Seafloor Massive Sulphides</b>	<b>Cobalt-Rich Crusts</b>
<i>Water depth</i>	4000-6000 m	1000-4000 m	800-2500 m
<i>Location of deposits</i>	Manganese nodules on the seabed of the deep ocean.	On the boundaries of oceanic plates, typically close to volcanic activity.	Crust layer on hard rock surfaces, typically on seamounts.
<i>Major components</i>	Co, Cu, Mn, Ni	Ag, Au, Cu, Zn	Co, Cu, Mn, Ni, REE

The main focus of deep-sea mining is currently polymetallic nodules (Chandrasekhar et al., 2024). Polymetallic nodules are rock concretions that lie at the bottom of the sea and are composed of layers of manganese hydroxides and iron (ISA, 2022). The exact chemical composition of the nodules varies, but they usually include the valuable minerals nickel, cobalt, and copper (ISA, 2022; MIDAS, 2017a). Polymetallic nodules were discovered in 1868 and the first trial of nodule mining technology took place in 1970 (ISA, 2022). CRCs and SMS were discovered and tested later (Cherkashov, 2022). Organisations in possession of an exploration contract are mainly testing the collection of polymetallic nodules (Chandrasekhar et al., 2024). The International Seabed Authority (ISA) is currently responsible for regulating deep-sea mining in international waters and has awarded 31 exploration contracts (ISA, 2025a). The ISA was formed by the United Nations Convention on the Law of the Sea (UNCLOS) and 169 states joined the institution (Baskaran & Schwartz, 2025). However, the United States never became a member of the ISA and President Trump recently revealed an executive order to secure the critical offshore minerals (Baskaran & Schwartz, 2025). In addition, the USA has the right to exploit the natural resources in the Exclusive Economic Zone (EEZ) of American Samoa, where polymetallic nodules are abundant (Deep Sea Mining, 2024). However, to date, commercial deep-sea mining has not been performed (Miller et al., 2021). Nevertheless, the deep-sea mining industry is pushing to start (Deep Sea Conservation Coalition, 2024).

Interest in deep-sea mining is growing due to the increasing demand for minerals that enable us to transition to clean energy technologies and the associated geopolitical tensions (Deep Sea Conservation Coalition, 2024; IEA, 2025b; Miller et al., 2021). The extraction of valuable minerals from the deep sea can support the realisation of a more sustainable and circular economy (Verma, 2023). In addition, polymetallic nodules contain a higher concentration of metals compared to land-based ores (Alvarenga et al., 2022). Furthermore, polymetallic nodules are softer than land-based ores, which makes grinding them less energy-intensive (Alvarenga et al., 2022). Another important reason for the growing interest in deep-sea mining is concerns about the geographical concentration of terrestrial minerals and the security of supply (IEA, 2025b). Lastly, interest in deep-sea mining is increasing because of the financial incentive that is expected to flow out of the extraction of the minerals (Miller et al., 2021).

While proponents are trying to convince the public of the benefits and necessity of deep-sea mining, opponents argue that there is not enough information on the negative impacts and risks (Deep Sea Conservation Coalition, 2024). The group of scientists, governments, coastal communities, indigenous groups, businesses, and civil society organizations that oppose deep-sea mining is growing (Deep Sea Conservation Coalition, 2024). Scientists and environmental groups, such as Greenpeace, are warning that deep-sea mining causes permanent damage to ecosystems and biodiversity (Greenpeace, 2025; Sharma & Smith, 2019). Some call for a complete prohibition, while others want a moratorium (precautionary pause) (Deep Sea Conservation Coalition, 2025). To date, 37 countries support this moratorium (Deep Sea Conservation Coalition, 2025). Opponents of deep-sea mining emphasize the need to gather more scientific information to make informed choices and prevent environmental damage (Deep Sea Conservation Coalition, 2024).

# 2

## Literature Review

This chapter discusses previous research on the potential environmental impacts of deep-sea polymetallic nodule collection. This leads to the research gap central to this study.

### **2.1. Potential Environmental Impacts**

Since the 1970s, numerous studies have been conducted to evaluate the potential environmental impacts of commercial deep-sea mining activities (Koschinsky et al., 2018; Sharma, 2015; Shirayama et al., 2017). These studies were carried out by monitoring impacts during mining tests or using simulation models of deep-sea mining activities (Koschinsky et al., 2018). Japan and India also conducted long-term monitoring research (Shirayama et al., 2017). In addition, Ma et al. (2019) composed numerical calculations. Furthermore, the pan-European initiative JPI Oceans has conducted two research projects on the environmental impacts of deep-seabed mining to inform the regulatory debate (JPI Oceans, 2024).

Previous research showed that polymetallic nodule collection potentially has a direct impact on species, biodiversity, and ecosystems (IUCN, 2024; Lins et al., 2021). The machine noise, vibration, and light are harmful to marine life and scraping across the seabed kills plants and animals (IUCN, 2024; JPI Oceans, 2022; Koschinsky et al., 2018). In addition, polymetallic nodules serve as substrates for several species (Koschinsky et al., 2018). The extraction of these nodules therefore causes permanent habitat destruction, which is harmful to the species (Koschinsky et al., 2018). Species that rely on nodules as substrates may disappear until the nodules are restored, which takes millions of years (Gollner et al., 2017). Marine biologist Diaz-Recio Lorenzo found that nodules from the Clarion Clipperton Zone (CCZ) typically carry 10 to 15 animals, and sometimes this number exceeds 200 (NIOZ, 2024).

In addition, the extraction of polymetallic nodules from the seabed causes sediment plumes that may have immediate and long-term environmental impacts (Weaver et al., 2022). For every tonne of nodules mined during exploitation, approximately 2.5-5.5 tonnes of sediment are disturbed and suspended (Fan et al., 2022). In addition to sediment plumes generated by mining vehicles on the seafloor, particle dispersion occurs through the release of waste materials during dewatering and pre-processing at the surface (JPI Oceans, 2022; MIDAS, 2017b). The particles in this return water can spread widely, especially in shallower waters (JPI Oceans, 2022). The study of JPI Oceans (2022) showed that sediment plumes cause displacement of fauna, but the survival, resettlement, and recovery of this fauna is still unknown. In addition, the plumes can contain contaminants that have toxic or harmful effects on organisms (JPI Oceans, 2022). However, questions remain about the threshold for organisms with respect to sediment thickness, plume concentration, and exposure time (Gazis et al., 2025).

Further, the research of JPI Oceans (2022) showed that other discharges to water could also have negative environmental impacts. The cooling water from deep-sea mining ships often contains chemicals (JPI Oceans, 2022). In addition, discharge of ballast water could cause spreading of invasive species that put existing ecosystems under stress, overgrow native species, or cause diseases (JPI Oceans, 2022).

After the two successful mining impact studies of JPI Oceans, the third project is scheduled to begin in July 2025 (JPI Oceans, 2024). This MiningImpact3 project aims to fill current knowledge gaps, better

understand the deep-sea environment and population, promote management and governance tools, and improve the comparison of environmental impacts of deep-sea and land-based mining (JPI Oceans, 2024).

## 2.2. LCA Studies

While previous research on polymetallic nodule collection focused on the potential environmental impacts, research on the potential life-cycle environmental impacts is scarce. This includes the environmental impacts across a product's life cycle (Guinée et al., 2002). So not only the extraction of the nodules, but also the transportation and processing of the minerals. Life Cycle Assessment (LCA) is a widely used method to assess these impacts, and it is expected to play an important role in decision making about deep-sea mining (Bolevich, 2021).

A study by Paulikas et al. (2020b), supported by The Metals Company (TMC), analysed the life-cycle impacts of the production of metals for Electric Vehicles (EVs) from deep-sea mined polymetallic nodules compared to that of land-based mining. This study included a wide range of life-cycle impact categories. In addition to environmental impacts, the study also included social and economic impacts. Therefore, this was the first attempt at a Life Cycle Sustainability Analysis (LCSA) of deep-sea mining. The results of this study showed that the potential impacts on climate change, land use, waste, and human and wildlife health are significantly lower for metals produced from polymetallic nodules. The authors argued that biodiversity loss is present for both mining alternatives, but they could not quantify these impacts.

As a follow-up, TMC commissioned Paulikas et al. (2020a) to carry out an LCA study focusing specifically on the impacts on climate change (The Metals Company, 2024b). This study again compared the impacts of the production of metals for EVs from polymetallic nodules to those of land-based ores. The results showed that the carbon footprint is lower when the metals come from polymetallic nodules, but the study did not consider other impact categories.

Furthermore, TMC commissioned Benchmark Mineral Intelligence (2022) to conduct a project-specific LCA study to compare the production of nickel, copper, and cobalt from polymetallic nodule collection and land-based mining. This study focused on TMC's NORI-D project. In this analysis, 21 environmental impact categories were included and polymetallic nodule collection had a lower potential impact for most of these categories.

A study by Alvarenga et al. (2022), supported by Global Sea Mineral Resources (GSR), also focused on the life-cycle impacts of the production of metals from polymetallic nodules in comparison with land deposits. This LCA study looked at the impacts on climate change, acidification, and photochemical oxidant formation. The results of this research showed that the photochemical oxidant formation impacts are the same for the two mining alternatives, while the potential climate change and acidification impacts are lower when the metals come from deep-sea nodules.

Lastly, research by Fritz et al. (2023), supported by the German Institute of Geosciences and Natural Resources (BGR), also assessed the life-cycle climate change impact of metals from polymetallic nodules compared to terrestrial mining. Similar to the LCA studies above, this research showed that the potential climate change impacts are lower when the metals come from polymetallic nodules. However, the authors argued that the results depend heavily on methodological choices and model inputs. The authors also stated that climate change should not be the impact category central to the discussion of deep-sea mining. They argued that the lower climate change impacts of deep-sea mining do not justify other concerning potential environmental impacts of deep-sea mining, such as impacts on biodiversity.

## 2.3. Research Gap

The previous LCA studies discussed in Section 2.2 differ in outcomes. Although all five studies concluded that the climate change impacts are lower for metals from polymetallic nodules than from land-based ores, there is a wide variation in values. Paulikas et al. (2020b) concluded a difference of about 70 percent, whereas Fritz et al. (2023) found a difference of 27 percent.

In addition, the previous LCA studies on metals from deep-sea nodules compared to land-based ores used different impact categories to draw conclusions about the environmental sustainability. The studies of Paulikas et al. (2020a) and Fritz et al. (2023) focused only on climate change. Levin

et al. (2020) emphasized that climate change impacts are important considerations in deep-sea mining decision-making, but Fritz et al. (2023) argued that other life-cycle environmental impacts should also be included in the discussion. The studies of Alvarenga et al. (2022), Benchmark Mineral Intelligence (2022), and Paulikas et al. (2020b), took into account, respectively, 3, 21, and 16 impact categories. However, the most concerning impacts on ecosystems and biodiversity loss are lacking in all LCA studies.

So, previous LCA studies showed a variation in results and focused on generic environmental impacts (mostly climate change), while overlooking other important impacts, such as those on biodiversity and ecosystems. At the same time, LCA studies are used to support claims that deep-sea mining outperforms land-based mining in terms of environmental impacts. For example, The Metals Company (2023a) stated that their nodule collection outperforms land-based mining in almost all impact categories analysed. However, they did not assess the impacts on biodiversity and ecosystems. In addition, policy makers are increasingly paying more attention to LCAs of metals (Metaxas et al., 2024). For example, this is the case for legislation from the European Commission on Critical Raw Materials, Corporate Sustainability Due Diligence, Batteries, and Sustainable Products (Metaxas et al., 2024).

In conclusion, previous LCA studies provided a starting point for evaluating the potential life-cycle environmental impacts of metals from deep-seabed mined polymetallic nodules compared to those from land-based ores. However, an aligned approach is missing, the results are varying, and concerning environmental impacts are not assessed. Nevertheless, these studies are used to show the public that deep-sea mining is better than land-based mining in terms of environmental impacts. To be able to make well-considered decisions about deep-sea mining, it is important to take a systematic approach, use LCA consciously, and acknowledge its limitations.

# 3

## Research Approach

This chapter presents the research approach of the study. First, the research objective and questions are introduced. Then, the methods and data requirements are discussed.

### 3.1. Research Objective

The objective of this research is to assess the potential environmental impacts throughout the life cycle of metals extracted from deep-sea polymetallic nodules, compared to those sourced from land-based ores. This seeks to provide a valid and transparent overview of these impacts to effectively inform policy and decision makers, scientists, and the public.

Specifically, the study seeks to evaluate the application of LCA in this context by analysing previous LCA studies, identifying the underlying causes of differences in their results, and exploring how LCA can support policy making and contribute to the ongoing debate on deep-sea mining. It is important to recognise that LCA focuses on generic environmental impacts and does not capture location-specific impacts on biodiversity and ecosystems, which are of key concern in deep-sea mining. For this reason, the study places greater emphasis on generic environmental impacts such as climate change, acknowledging that biodiversity-related impacts fall outside of what LCA can adequately evaluate. In addition, this study aims to highlight key limitations and uncertainties relevant to the debate.

### 3.2. Research Question

To fill the research gap and fulfill the research objective, the following research question aims to be answered in this study:

**How can LCA be used to support (policy) decisions on mining metals from deep-sea polymetallic nodules compared to land-based mining, and what are its main limitations in this context?**

This research question is divided into the following sub-research questions:

1. What are the outcomes of previous LCA studies on metals from deep-sea polymetallic nodules compared to land-based mining?
2. What are the most significant causes of differences in the outcomes of these LCAs?
3. How can these previous LCAs be aligned?
4. What can be concluded from this aligned LCA with regard to the life-cycle environmental impacts?
5. What are the main limitations of LCA in this context, and how can they be addressed?

### 3.3. Methods & Data Requirements

First, before comparing the previous LCA studies, the mining value chain of deep-sea mining of polymetallic nodules is discussed. This provides a clearer understanding of the different stages involved, from extraction to metal refining.

Then, a comparative analysis of the previous LCA studies is performed. This adopts a similar approach to that of Van der Voet et al. (2010), which focused on differences in LCAs on biofuels. The comparative analysis begins with a review of the outcomes of the previous LCAs to identify differences, addressing the first sub-research question in Section 3.2. Following this, the study analyses how these LCAs were carried out by identifying and comparing methodological choices, key assumptions, and data used. Details are extracted from appendices, supplementary materials, and additional information gathered by contacting the authors directly. Similar to Van der Voet et al. (2010), the comparative analysis is structured in line with the LCA methodology outlined by Guinée et al. (2002), which is based on the ISO 14040 framework. This framework consists of four iterative phases: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment, and 4) Interpretation (Guinée et al., 2002). The previous LCA studies are reviewed for each of these four steps. The purpose of this part of the research is to explain the differences in outcomes with differences in how the LCAs were conducted, thereby answering the second sub-research question.

Subsequently, the previous LCA studies are aligned into one LCA model. This new LCA is based on the most appropriate methodological choices, assumptions, and data, identified in the comparative analysis, supplemented by additional literature and recent developments in the field. Therefore, the main data sources for this LCA are the previous LCA studies. Furthermore, OpenLCA software is used for modelling (GreenDelta, 2025). The results of this aligned LCA are then analysed to draw conclusions about the life-cycle environmental impacts and the influence of specific modelling choices, addressing sub-research questions 3 and 4 (Section 3.2).

Lastly, to address the final sub-research question, the study identifies the most significant limitations. This includes, among others, the lack of biodiversity impacts in LCA. This discussion is based on recent literature and highlights key considerations, uncertainties, and potential opportunities. The aim is to provide policy and decision makers with a more comprehensive understanding of the broader circumstances and to support future research in this field.

The main research question is answered by integrating the findings of all sub-research. This leads to conclusions and recommendations that support policy making and the ongoing debate on deep-sea mining of polymetallic nodules.

The next four chapters of this report include respectively the mining value chain, the comparative analysis, the aligned LCA, and the discussion. The study ends with conclusions and recommendations.

# 4

## Mining Value Chain

This chapter explains the mining value chain of metals from deep-seabed mined polymetallic nodules. The different steps in the value chain are discussed to provide context and a better understanding of deep-sea mining before reviewing the previous LCA studies in Chapter 5.

Ecorys et al. (2014) identified several phases within the deep-sea mining value chain, as illustrated in Figure 4.1. This section provides an explanation of these phases. Four phases are highlighted in light grey to illustrate their exclusion from the system boundaries of the LCA studies, as further elaborated in Chapter 5.



Figure 4.1: Mining value chain of deep-sea mining, adapted from Ecorys et al. (2014) and Environment Foundation (2018).

### Prospecting

In the prospecting phase, areas likely to contain polymetallic nodules are identified (Environment Foundation, 2018). This phase includes geochemical, geological, and geophysical surveys, such as multibeam swath bathymetry (Environment Foundation, 2018). The steps after the prospecting phase become increasingly more detailed and the uncertainty about the resource decreases. The prospecting phase is characterized by a rough search and significant uncertainty regarding the resource.

### Exploration

The purpose of the exploration phase is to locate the nodules and assess their characteristics (Ecorys et al., 2014). The composition of the nodules and the density of the metals are obtained by sampling (Ecorys et al., 2014). The Joint Ore Reserves Committee (JORC) Code, a standardized framework for reporting exploration results on ore reserves and mineral resources, is commonly applied during and after this phase (JORC, 2024). Compared to the prospecting phase, the exploration entails a more detailed search with reduced uncertainty regarding the resource.

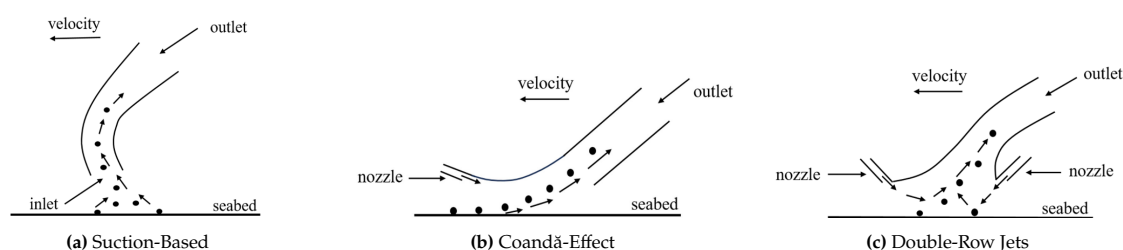
### Resource Assessment, Evaluation & Planning

This phase aims to assess and evaluate the technological, metallurgical, economic, social, legal, governmental, and environmental feasibility (Ecorys et al., 2014). This step also involves the planning of subsequent phases within the value chain. The stages outlined from prospecting to planning are necessary steps that must be completed before mining can start and capital can be acquired.

## Extraction, Lifting & Surface Operations

In this phase, the exploitation of the nodules begins (Ecorys et al., 2014). First, **extraction** takes place with a nodule collector. As explained by Liu et al. (2024), nodule collection technologies are categorized into mechanical, hydraulic, and mechanical-hydraulic technologies. Mechanical technologies primarily rely on mechanical structures, such as shovels, brushes, and rakes, to extract the nodules. Hydraulic technologies use water jets to lift and remove the nodules from the seabed. Lastly, mechanical-hydraulic collection technologies combine elements of both structures.

Among these, hydraulic collection technologies are the most advanced, having been tested successfully at production speeds in deep-sea conditions (Cheng et al., 2023; Liu et al., 2024). Liu et al. (2024) further classify hydraulic collection into three main types: suction-based, Coandă-effect-based, and double-row jets. As explained by the authors, the suction-based technology uses a suction pump to lift the nodules and transport them to the upper pipe of the system. The Coandă-effect technology utilizes the phenomenon discovered by Henri Coandă, which ensures that a jet stream adheres to a surface even when the surface curves (Alhaddad et al., 2023). Lastly, the double-row jets technology consists of two rows of nozzles that eject jets that hit the seabed in an oblique direction, converging and rising in the middle, so that the surrounding fluids converge and flow upward into the collection pipe (Liu et al., 2024). A schematic representation of these different types of hydraulic collection technologies is presented in Figure 4.2.



**Figure 4.2:** Schematic representation of different types of hydraulic collection technologies, from Liu et al. (2024)

After extraction, the nodules undergo **vertical transport** to bring them to the surface. Schott et al. (2024) distinguish the following vertical transport systems as the most prominent: mechanical lift, airlift, and hydraulic lift. The mechanical lifting system mainly uses carrier lifting and line bucket lifting to bring the nodules to the surface (Hu et al., 2022). The airlift system is a pipe lifting system that consists of an air compressor on the mining vessel and high pressure air injection into the lifting pipe (Hu et al., 2022). This creates an upward water flow that lifts the nodules by overcoming their settling velocity (Hu et al., 2022). Lastly, the hydraulic lift system is a closed system with a surface pump that pumps seawater as the transfer fluid, moving the nodules to the surface via a riser pump (Hu et al., 2022).

Furthermore, this phase involves surface operations that are provided by a production support vessel (PSV) (Ecorys et al., 2014). This vessel can function as storage facility, dispatching system, or pre-processing facility (Ecorys et al., 2014). **Offshore pre-processing** typically includes dewatering, rotary screening, and hydrocycloning to enable safe storage on the vessel, reduce transport weight, and secure vessel stability by preventing sloshing (Alvarenga et al., 2022; Ecorys et al., 2014; Helmons et al., 2022). The initial mixture that undergoes offshore pre-processing consists of ore, sediment, and water (Helmons et al., 2022). After pre-processing, the large nodule parts are stored on the vessel. Sediment, water, and fine-grained nodules that cannot be recovered by centrifugation and sieving are discharged to the subsea, creating a plume (Helmons et al., 2022). The discharge can take place at different depths. For instance, TMC uses a return depth of 1,200 meters for their NORI system (NORI, 2022). On the other hand, GSR assumes that sediment discharge takes place close to the seabed (GSR, 2023). There is an ongoing debate on the optimal discharge depth to minimize the environmental impacts of sediment plumes (Drazen et al., 2020; Helmons et al., 2022).

## Offshore & Onshore Logistics

Subsequently, the raw or pre-processed nodules are transported to the onshore processing site (Ecorys et al., 2014). The **offshore horizontal transport** is conducted by ships. This is typically done with "traditional" bulk carriers, but it can also be carried out using the same vessels employed for nodule

extraction (Ecorys et al., 2014). For instance, Impossible Metals makes use of a system called Shuttle Transport and Resupply Ships (STARS), which is a fleet of ships that shuttle continuously between the offshore extraction site and the onshore port (Impossible Metals, 2025a).

After the offshore horizontal transport from the extraction site to a port, **onshore horizontal transport** may be necessary, depending on the location of the processing plant. If the plant is located next to the port, no further transport is required. Otherwise, transportation may involve trucks, trains, inland shipping, or transshipment (port-to-port).

### **Processing & Refining**

In this phase, the nodules are processed and refined to the final metal products. This process begins with **pre-processing**, which may include steps such as comminution to grind the nodules into smaller particles (Ochromowicz et al., 2021). This is followed by **processing & refining**, for which several techniques and processing routes are available (Ecorys et al., 2014). These methods are generally classified into hydrometallurgical (water-based) and pyrometallurgical (heat-based) processes (Ochromowicz et al., 2021). Hydrometallurgical processes include methods such as leaching, while pyrometallurgical processes typically involve smelting (Ochromowicz et al., 2021).

### **Distribution & Sales**

The final phase of the mining value chain is the distribution and sale of the refined metals. While this phase is not relevant from a technology perspective, it is important in terms of economic value (Ecorys et al., 2014).

# 5

## Comparative Analysis

This chapter involves the comparative analysis of the five previous LCA studies on metals from deep-sea polymetallic nodules compared to land-based mining. The studies included in this analysis are the only published LCAs on polymetallic nodules to date, as presented in Section 2.2. An overview of these studies is also given in Table 5.1.

**Table 5.1:** The LCA studies of the comparative analysis

	<i>Authors</i>	<i>Year</i>	<i>Title</i>	<i>Supported by</i>	<i>Public/Private</i>	<i>Sponsoring state</i>
1	Paulikas, Katona, Ilves, Stone, and O’Sullivan.	2020b	Where should metals for the green transition come from?	The Metals Company (TMC)	Private	Nauru
2	Paulikas, Katona, Ilves, and Ali.	2020a	Life cycle climate change impacts of producing battery metals from land-based ores versus deep-sea polymetallic nodules.	The Metals Company (TMC)	Private	Nauru
3	Benchmark Mineral Intelligence	2022	Life Cycle Assessment for TMC’s NORI-D polymetallic nodule project and comparison to key land-based routes for producing nickel, cobalt and copper.	The Metals Company (TMC)	Private	Nauru
4	Alvarenga, Pr��at, Duhayon, and Dewulf.	2022	Prospective life cycle assessment of metal commodities obtained from deep-sea polymetallic nodules.	Global Sea Mineral Resources (GSR)	Private	Belgium
5	Fritz, Heidak, Vasters, Kuhn, Franken, and Schmidt.	2023	Life cycle impact on climate change caused by metal production from deep sea manganese nodules versus land-based deposits.	German Institute of Geosciences and Natural Resources (BGR)	Public	Germany

Table 5.1 shows that the first three studies are supported by TMC. This is a publicly traded company with foreign sponsoring states (Nauru, Kiribati, Tonga) (The Metals Company, 2024a, 2024d). TMC operates through the Nauru Ocean Resources Inc. (NORI) subsidiary, which is sponsored by the Republic of Nauru (The Metals Company, 2024d). Nauru is a proponent of deep-sea mining and sees it as an important opportunity for transitioning to renewable energy (Cagurangan, 2024). The president of Nauru stated that the biggest risk is not the potential environmental impact, but rather the risk of missing this opportunity (Cagurangan, 2024).

Furthermore, Alvarenga et al. (2022) are supported by GSR, which is a subsidiary of Dredging, Environmental and Marine Engineering NV (DEME), a Belgian marine, environmental, and dredging engineering group (DSMA, 2019). Belgium takes a middle-ground position, supporting deep-sea mining under strict rules and with environmental safeguarding (Dewulf, 2024).

Lastly, Fritz et al. (2023) are supported by the BGR, which is part of the German Federal Ministry of Economic Affairs and Energy (BMWK, 2025). Thus, TMC and GSR are commercially driven, whereas BGR is a public institution. Similar to Belgium, Germany takes a middle ground position, supporting deep-sea mining under strict conditions (Dewulf, 2024).

This chapter first reviews and compares the outcomes of the studies, then analyses how the LCAs were conducted and the choices made by the researchers (i.e., the LCA model choices). Finally, it explains how differences in model choices led to different results. The comparative analyses focuses mainly on climate change, as this is the only impact category assessed in all studies and is therefore comparable. This does not imply that this category is more important than others. Moreover, because the LCAs do not cover impacts on biodiversity and ecosystems, these are also missing from the comparative analysis, despite being particularly relevant to deep-sea mining. The comparative analysis is based on published reports, supplementary documents, and additional information provided by the authors upon request.

## 5.1. Outcomes

This section reviews and compares the different outcomes of the studies. This includes the characterization results, contribution analysis, and the conclusions & recommendations of the studies.

### 5.1.1. Characterization Results

Characterization involves the classification of the environmental flows into specific impact categories and quantifying them in a common unit per category (Guinée et al., 2002). The characterization results are compared by examining the percentage differences for each category. This percentage difference between the two alternatives is calculated using the following formula with land-based normalization:

$$\frac{\text{impact value of DSM alternative} - \text{impact value of land-based alternative}}{\text{impact value of land-based alternative}} \times 100\%$$

These percentages can be compared between studies even though the studies used different reference flows, because the percentages present the relative difference between the alternatives. There is a wide variation in the percentage difference of the climate change impacts (GWP) between the nodules and land-based ores. The impact values and the percentage differences are presented in Table 5.2.

**Table 5.2:** Climate change (GWP) comparison of metals from deep-sea and land-based mining.

No.	Authors	Unit	DSM	Land	% Difference	Reference flow	Comment
1-2	Paulikas et al. (2020b, 2020a)	Mt CO <sub>2</sub> -eq	4.5E+02	1.9E+03	-75.9%	For 1 billion EVs <sup>a</sup>	Baseline land-ores scenario
			4.5E+02	1.5E+03	-69.7%	For 1 billion EVs <sup>a</sup>	Green land-ores scenario
3	Benchmark Mineral Intelligence (2022)	kg CO <sub>2</sub> -eq	4.9E+00	1.3E+01	-61.2%	For 1 kg Ni/Cu/Co matte	
		kg CO <sub>2</sub> -eq	6.2E+00	2.8E+01	-78.3%	For 1 kg Ni in Nickel sulphate	
		kg CO <sub>2</sub> -eq	1.6E+01	6.3E+01	-73.8%	For 1 kg Co in Cobalt sulphate	
		kg CO <sub>2</sub> -eq	2.8E+00	1.2E+01	-76.5%	For 1 kg Cu cathode	
4	Alvarenga et al. (2022)	kg CO <sub>2</sub> -eq	1.4E+03	2.2E+03	-37.5%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	Scenario A
		kg CO <sub>2</sub> -eq	1.8E+03	2.2E+03	-16.5%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	Scenario B
5	Fritz et al. (2023)	kg CO <sub>2</sub> -eq	2.0E+00	2.8E+00	-27.0%	For 15.3 g Ni, 11.7 g Cu, 2.2 g Co, and 338 g FeMn.	

<sup>a</sup> The EV is assumed to be a Tesla Model 3 requiring 56.2 kg Ni, 85 kg Cu, 7.05 kg Co, and 6.6 kg Mn per car.

The percentage differences in Table 5.2 are all negative, showing that the impacts of metals from deep-sea nodules are lower compared to land-based mining. These differences range from -16.5% to -78.3%. The studies by Alvarenga et al. (2022) and Fritz et al. (2023) show relatively low percentages, while the studies by Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b, 2020a) show higher percentages, indicating that the deep-sea alternative is more beneficial. Note that the first two studies of Paulikas et al. (2020b, 2020a) have the same characterization results. Although these are two separate publications, they were conducted by almost the same authors using the same LCA model.

In addition, both Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b) analysed the impacts on ecotoxicity, eutrophication, human toxicity, land use, water use, and energy resource scarcity. Both studies concluded that the land-based mining alternative has higher impacts in these categories. Applying the formula above to these categories shows that the two studies have similar percentage differences, except for energy resource scarcity. In this category, the outcomes of Benchmark Mineral Intelligence (2022) result in percentage differences in the range of -66% to -79%, whereas the outcomes of Paulikas et al. (2020b) show a percentage difference of -3% for the baseline land-ores scenario and +3% for the green land-ores scenario. Thus, in the latter scenario, Paulikas et al. (2020b) actually concluded that the land-based ores alternative outperforms the deep-sea nodules alternative in terms of energy resource impact. The explanation for this difference in results is discussed in Section 5.3.

### 5.1.2. Contribution Analysis

All studies concluded that onshore processes, specifically pyrometallurgical processing, contribute the most to the climate change impacts of the deep-sea mining alternative. This is mainly due to the energy-intensiveness of this process. In addition, even though the studies assumed different offshore processes (see Section 5.2.2), they all found that offshore processes contribute relatively little to the climate change impacts.

In contrast, the results of Paulikas et al. (2020b, 2020a) showed that for the land-based mining alternative, mining and concentration processes account for about half of the climate change impacts. This is primarily due to the energy use. The other studies also concluded that energy consumption is the main contributor to the climate change impacts. For Benchmark Mineral Intelligence (2022), this is because their analysis assumed that the extraction of land-based ores takes place in Australia, which has a carbon-intensive energy mix. Additionally, Fritz et al. (2023) assumed that the land-based mining takes place in Finland (Kevitsa project) and Australia (Murrin Murrin and Woodie Woodie projects), as will be explained in Section 5.2.3. In this study, the main contributors to the climate change impacts of the Kevitsa project (for Ni) and the Murrin Murrin project (for Ni/Co) were also the use of electricity, diesel, and natural gas. In addition, for the Kevitsa project, metallurgical processes contributed relatively little to the climate change impacts, due to the high share of hydropower in the electricity mix of Finland. On the other hand, for the Woodie Woodie project (for FeMn), pyrometallurgical processing was the main contributor to the climate change impacts, similar to the deep-sea nodule alternative.

Furthermore, the study of Benchmark Mineral Intelligence (2022) concluded that the production of sulphidic tailings is the main contributor to impacts on human health and freshwater eutrophication in the land-based mining alternative. In contrast, the deep-sea mining alternative does not produce these tailings. Furthermore, this study showed that the blasting process in the land-based alternative contributes most to particulate matter formation, ozone depletion, and terrestrial acidification. Blasting is a process that breaks rock loose with explosives (Balasubramanian, 2017). While this process is used in land-based mining, it is not required for deep-sea mining of polymetallic nodules, because the nodules lie loose on the seabed and can be collected without explosives.

### 5.1.3. Conclusions & Recommendations of the Studies

All studies concluded that the production of metals from polymetallic nodules potentially has environmental advantages over metals from land-based ores. In addition, Paulikas et al. (2020b, 2020a) concluded that the potential climate change impacts are significantly lower for the deep-sea alternative, due to lower energy requirements and easy access to hydropower or other renewables. They explained that there is flexibility in locating nodule processing plants near a port, allowing access to hydropower, other renewable energy sources, by-products, and markets. In contrast, the authors stated that land-based mining requires a processing plant close to the mine, due to the high mass of the ores. This is also what they assumed for land-based mining in their LCA.

The same conclusions about energy consumption hold for the study by Benchmark Mineral Intelligence (2022). Although they did not assume a nodule processing plant directly next to the port, they assumed Texas as the processing location, where renewable electricity is highly available. They concluded that the use of renewables in the deep-sea mining alternative plays an important role in outperforming the land-based alternative on climate change impacts. In addition, they concluded that the higher ore grades of polymetallic nodules, meaning a higher concentration of the desired metal in the ore, also play an important role in this advantage by reducing energy use.

Alvarenga et al. (2022) also concluded that a clean energy supply for onshore processing of the nodules is important for the environmental performance of this alternative. Although this study did not assume 100% renewable energy, as will be explained in Section 5.2.2, they stated that better environmental performance could be achieved by locating the processing plant in a region with a high share of renewables in the grid or by directly purchasing renewable energy.

Furthermore, Fritz et al. (2023) concluded that the difference in climate change impacts between the alternatives depends on the methodological choices and model inputs. Moreover, they recommended that decision making about deep-sea mining should not be based solely on climate change.

Lastly, Paulikas et al. (2020b) concluded that the impact on seafloor use would be much higher for deep-sea mining. Therefore, the authors stated that the main advantage of land-based mining is the avoidance of disturbing a large area of which we have insufficient knowledge. They recommended further assessments of the environmental impacts on ecosystem function and sea life.

## 5.2. LCA Model Choices

LCA model choices involve how the studies were conducted, assumptions, and data. This section covers goal & scope definitions, life-cycle inventory analysis, and life-cycle-impact assessment, following the ISO framework (Guinée et al., 2002). In addition, the sensitivity analyses are reviewed.

### 5.2.1. Goal & Scope Definitions

Although formulated differently, all five LCA studies share a similar **goal** and **system boundary**. The main objective of the studies was to analyse the environmental impacts of metals from deep-sea polymetallic nodules compared to terrestrial mining. Paulikas et al. (2020a) specified this for only climate change impacts, while Paulikas et al. (2020b) also considered social and economic impacts. In addition, all studies considered a cradle-to-gate analysis, thus from resource extraction to metal refining.

The **geographical scope** of the LCA studies is similar for nodule extraction, but differs for the processing sites. All LCAs focused on the CCZ of the Pacific Ocean for the extraction of nodules. This region is shown in red in Figure 5.1, with the NORI-D area highlighted with a red pin. For processing, Fritz et al. (2023) assumed Lázaro Cárdenas, Mexico (orange pin), while Benchmark Mineral Intelligence (2022) assumed Texas (blue pin). Furthermore, Paulikas et al. (2020b, 2020a) did not specify the exact location of the processing plant, but assumed that it is near the port (orange pin).

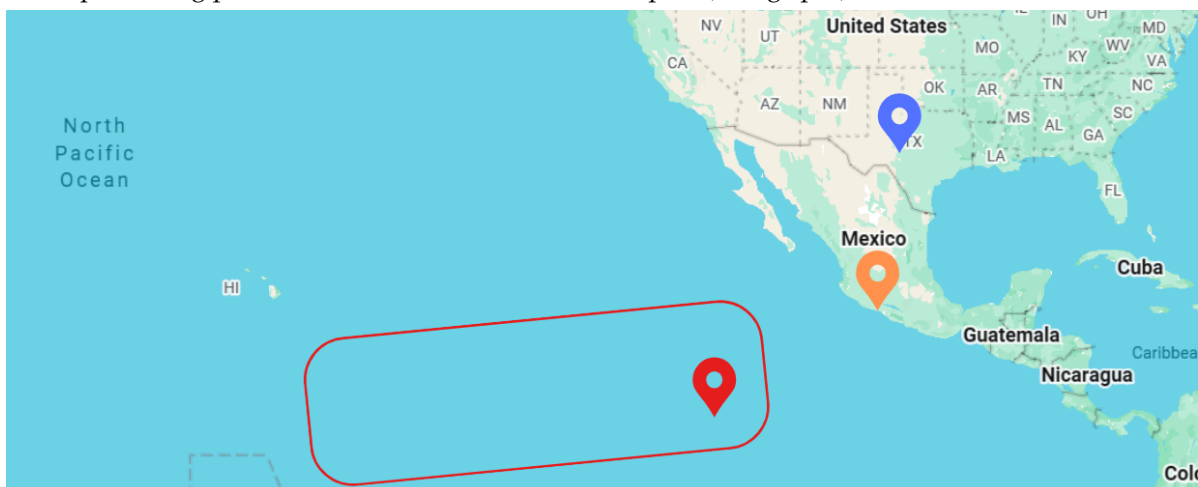


Figure 5.1: Locations of the extraction (red) and processing (orange & blue) of the nodules in the LCAs, based on Gales (2023a).

In addition, Alvarenga et al. (2022) kept the exact locations of the nodule processing plants confidential but distinguished two scenarios. For Scenario A, the location of the plant is 4010 km from the exploitation site, and for Scenario B this is 2000 km. Moreover, the location in Scenario A has an electricity mix with 85% hydropower, while Scenario B has a mix with fewer renewables (55% natural gas).

The geographical scope for land-based mining also differs among the studies. Fritz et al. (2023) considered sites in Finland (Kevitsa project) and Australia (Murrin Murrin and Woodie Woodie projects). Benchmark Mineral Intelligence (2022) assumed extraction in Australia and refining in China for conventional mining. The other LCAs used global averages or combinations of production routes.

Although all studies adopted a prospective approach for the deep-sea mining system, there is variation in the **temporal scope**. Paulikas et al. (2020b, 2020a) calculated impacts over the period 2017 to 2047. For land-based mining, they modeled two future scenarios, while for deep-sea mining they used a single fixed scenario across the entire time frame. Furthermore, for land-based mining, Alvarenga et al. (2022) used datasets for the production of copper, nickel, and cobalt from 2013, 2011, and 2012 respectively. Finally, the temporal scope of all studies depends on the Ecoinvent version that was used for the background data, which ranges from 2010 (Ecoinvent v2.2) to 2021 (Ecoinvent v3.8).

The **technological scope** of the studies is based on different DSM systems. Paulikas et al. (2020b, 2020a) assumed the system of TMC, including the collection technology of Allseas, the riser technology of Deep Reach Technologies, and the processing technologies of Hatch. In addition, Benchmark Mineral Intelligence (2022) assumed the technologies used in TMC's NORI-D project. Alvarenga et al. (2022) assumed the GSR collector, which is compatible with TMC. Fritz et al. (2023) based their system on the studies of Heinrich et al. (2020) and Kirchain et al. (2019) and used the study of Dames & Moore and EIC Corporation (1977) for the basic metallurgical processes. For the land-based alternative, the studies assumed conventional mining as modelled in Ecoinvent or as assumed to be reliable and available.

The studies defined different **functions, functional units, and reference flows**. Paulikas et al. (2020b) included nickel, copper, cobalt, and manganese, while Alvarenga et al. (2022) and Fritz et al. (2023) used ferromanganese instead of manganese. Benchmark Mineral Intelligence (2022) only included nickel, copper, and cobalt. Moreover, all studies except Benchmark Mineral Intelligence (2022) applied a "basket approach", conducting an LCA for the group of metals. In contrast, Benchmark Mineral Intelligence (2022) conducted separate LCAs for each metal. Notably, they initially also included MnSi as a reference flow but excluded it from the comparison. The studies also differ in the quantities used in the reference flows. Alvarenga et al. (2022) and Fritz et al. (2023) based the amounts on nodule compositions, whereas Paulikas et al. (2020b, 2020a) based them on electric vehicle requirements, resulting in significantly less manganese. Consequently, 95% of the manganese slag, including the environmental impacts of its downstream processes, is excluded. The reference flows are presented in Table 5.3.

Table 5.3: Reference flows of the previous LCA studies

		<i>Reference flow deep-sea alternative</i>	<i>Reference flow land-based alternative</i>
1-2	Paulikas et al. (2020b, 2020a)	Metals for 1 billion EVs produced from <b>deep-sea mined polymetallic nodules</b> by 2047. <sup>a</sup>	Metals for 1 billion EVs produced from <b>land-based mined ores</b> by 2047. <sup>a</sup>
3	Benchmark Mineral Intelligence (2022)	<ul style="list-style-type: none"> <li>• 1 kg of Ni/Cu/Co matte from <b>TMC's NORI-D collection</b>.</li> <li>• 1 kg of Ni in nickel sulphate from <b>TMC's NORI-D collection</b>.</li> <li>• 1 kg of Co in cobalt sulphate from <b>TMC's NORI-D collection</b>.</li> <li>• 1 kg of Cu cathode from <b>TMC's NORI-D collection</b>.</li> </ul>	<ul style="list-style-type: none"> <li>• 1 kg of Ni/Cu/Co matte from <b>dominant terrestrial routes</b>.</li> <li>• 1 kg of Ni in nickel sulphate from <b>dominant terrestrial routes</b>.</li> <li>• 1 kg of Co in cobalt sulphate from <b>dominant terrestrial routes</b>.</li> <li>• 1 kg of Cu cathode from <b>dominant terrestrial routes</b>.</li> </ul>
4	Alvarenga et al. (2022)	One unit of commodities (12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn) from <b>deep-sea mining</b> , delivered to market.	One unit of commodities (12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn) from <b>terrestrial mining</b> , delivered to market.
5	Fritz et al. (2023)	One unit of metals (15.3 g Ni, 11.7 g Cu, 2.2 g Co, 338 g FeMn) from <b>deep-sea mining</b> , provided to industry.	One unit of metals (15.3 g Ni, 11.7 g Cu, 2.2 g Co, 338 g FeMn) from <b>land-based mining</b> , provided to industry.

<sup>a</sup> The EV is assumed to be a Tesla Model 3 requiring 56.2 kg Ni, 85 kg Cu, 7.05 kg Co, and 6.6 kg Mn per car.

### 5.2.2. Life-Cycle Inventory Analysis DSM Alternative

The studies considered similar foreground processes for the deep-sea mining system, but the specific technologies, methods, and input and output values of these foreground processes differ. Table 5.4 presents an overview of the Life Cycle Inventory (LCI) model specifications for the five previous LCA studies. This table covers different phases of the mining value chain discussed in Chapter 4.

For this comparative analysis, the input and output values of the processes of all studies are scaled to 1 tonne of dry nodules to enable comparison between the LCAs. Otherwise, comparison is not possible, as the studies assume different reference flows (see Table 5.3) and different ore grades. A complete overview of the scaled input and output values is presented in Appendix B.3.

The scaled input values of the total energy input for the excavation and transportation processes are converted to kWh for each LCA. Table 5.4 shows that Alvarenga et al. (2022) assumed the highest total energy input of 470 kWh for 1 tonne of dry nodules for Scenario A. This is also the scenario with the largest distance between the exploitation and processing sites. In contrast, the table shows that Paulikas et al. (2020b, 2020a) assumed the lowest total energy input for excavation and transportation.

Furthermore, Table 5.4 shows that all studies considered a combination of pyro- and hydrometallurgical processes for processing and refining. However, the specific processing routes assumed by the studies differ. The processing route of Alvarenga et al. (2022) consists mainly of hydrometallurgical processes, with smelting of MnFeOx being the only pyrometallurgical process they included. The other studies considered more pyrometallurgical processes, such as rotary kiln calcining and coke reduction. Additionally, all studies included smelting in their processing routes, and all assumed an electric furnace for this pyrometallurgical process. Benchmark Mineral Intelligence (2022) further clarified that 88% of the electricity for processing is consumed by the furnace.

In addition, the table shows that Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b, 2020a) modelled approximately the same electricity input for processing and refining of about 500 kWh for 1 tonne of dry nodules. On the other hand, Alvarenga et al. (2022) and Fritz et al. (2023) assumed a higher electricity input.

Furthermore, Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b, 2020a) assumed that the electricity input is fully provided by renewable energy, whereas Alvarenga et al. (2022) and Fritz et al. (2023) assumed electricity mixes with fossil fuels. Fritz et al. (2023) criticised the optimistic assumption made by Paulikas et al. (2020a). They argued that even in countries with a lot of hydropower, a processing plant would still compete with other electricity users and could push them toward more polluting sources. They agreed that low-carbon electricity is feasible, but emphasized that such options are also available for land-based mining.

In addition, the studies modelled similar types of outflows for the processing and refining processes. For instance, the studies reported similar mineral outputs (Ni, Cu, Co, Fe, and Mn). However, as shown in Table 5.4, the studies modelled different CO<sub>2</sub> outflows for these foreground processes. Fritz et al. (2023) assumed significant larger CO<sub>2</sub> emissions than Alvarenga et al. (2022) and Paulikas et al. (2020b, 2020a). Besides, Benchmark Mineral Intelligence (2022) did not report any CO<sub>2</sub> outflow, so they only took into account the CO<sub>2</sub> emissions from the background processes.

Lastly, most studies use the economic allocation method to address multifunctionality. As argued by Fritz et al. (2023) and Paulikas et al. (2020b, 2020a), this allocation method is commonly used in LCAs about metals. However, for the coal-based reduction and Mn sulfate production processes, Paulikas et al. (2020b, 2020a) used physical allocation because, in this process, carbon binds stoichiometrically to oxygen. Further, Alvarenga et al. (2022) used the substitution approach to address multifunctionality. Thus, they subtracted the burdens of an alternative technology for generating energy to address the energy surplus. In addition, they assumed that the by-products with a low market value are burden-free, so that no allocation method was necessary. Lastly, Benchmark Mineral Intelligence (2022) assumed physical allocation for the pyrometallurgical processes, economic allocation for the hydrometallurgical processes, and system expansion for the converter slag and ammonium sulphate by-product. Since this is the only study that did not use a "basket approach" but analysed the metals separately, allocation amongst the metals was necessary.

**Table 5.4:** Comparison of the LCI model for the DSM alternative of the five previous LCAs

Process / Aspect	<i>Paulikas et al. (2020b, 2020a)</i>	<i>Benchmark (2022)</i>	<i>Alvarenga et al. (2022)</i>	<i>Fritz et al. (2023)</i>
<b>Extraction</b>	Coandă-effect	Coandă-effect	Coandă-effect	Not specified
<b>Vertical transport</b>	Air lift	Air lift	Hydraulic lift	Hydraulic lift
<b>Offshore pre-processing</b>	Not specified	Not specified	Rotary screening, hydrocycloning, and dewatering.	Not specified
<b>Offshore horizontal transport</b>	Vessel ~2,000 km	Vessel ~2,000 km	Vessel ~4,010 km (Scenario A) ~2,000 km (Scenario B)	Vessel ~2,000 km
<b>Onshore horizontal transport</b>	None	Transshipment Panamax	Rail transport	None
<b>Energy input excavation &amp; transport<sup>a</sup></b>	115 kWh	418 kWh	470 kWh (Scenario A) 356 kWh (Scenario B)	271 kWh
<b>Onshore pre-processing</b>	Comminution	Comminution (after pyro)	Comminution	Comminution
<b>Processing &amp; Refining</b>	Pyro- and hydrometallurgical	Pyro- and hydrometallurgical	Mainly hydrometallurgical	Pyro- and hydrometallurgical
<b>Electricity input processing &amp; refining<sup>a</sup></b>	497 kWh	515 kWh	2,539 kWh	834 kWh
<b>Electricity source processing &amp; refining</b>	100% Hydropower	100% Wind power	Mix with 85% hydropower (A) Mix with 55% natural gas (B)	Mexican grid (>50% fossil)
<b>Water input processing &amp; refining<sup>a</sup></b>	Not specified	1,738 m <sup>3</sup>	4,521 m <sup>3</sup>	3,947 m <sup>3</sup>
<b>Silica sand/flux input processing &amp; refining<sup>a</sup></b>	88 kg	83 kg	Not specified	280 kg
<b>CO<sub>2</sub> emissions processing &amp; refining<sup>a</sup></b>	328 kg	Not specified	138 kg	1,105 kg
<b>Ecoinvent version</b>	v2.2	v3.8	v3.5	v3.7.1
<b>Multifunctionality</b>	Economic allocation (mainly) & Physical allocation	Economic allocation, Physical allocation & System expansion	Substitution approach	Economic allocation

<sup>a</sup> Values scaled to 1 tonne of dry nodules to compare between studies, see Appendix B.3 for calculations.

### 5.2.3. Life-Cycle Inventory Analysis Land-Based Mining Alternative

The previous LCA studies based their land-based mining systems on secondary data. **Paulikas et al. (2020b, 2020a)** used published production routes for each metal, made adjustments to these models, and weighted the different routes based on the estimated proportion of metals used in batteries. The 10 production routes are explained in detail in the supplementary document of Paulikas et al. (2020a). They included different mining types (open-pit or underground) and different processing routes (pyrometallurgical or hydrometallurgical). The authors explained that land-based mining requires roughly four times more ore than deep-sea mining, due to the higher ore grades of polymetallic nodules, which in turn leads to higher energy demand to produce the same amount of metal.

In addition, **Benchmark Mineral Intelligence (2022)** selected a variety of production routes to separately compare with the deep-sea alternative. In this comparative analysis, only the conventional production route is considered, since this route is applicable to all metal types in the study. This is necessary because this study did not take a "basket approach", as explained before. The processing technologies of the conventional route are Pierce-Smith converters and flash furnaces. The authors reported that the total electricity consumption of the land-based mining model is three times larger than that of the deep-sea mining model, because the higher ore grades of polymetallic nodules significantly reduce energy demand.

Furthermore, **Alvarenga et al. (2022)** used the Gabi v8.7 database for FeMn production and generic data from metal commodity associations for the other metals. For nickel, they used global average production of the year 2011 from the Nickel Institute. For copper, they used global average production of the year 2013 from Copper Alliance. Lastly, for cobalt, they used average production of the year 2012 from the Cobalt Institute. Similar to the studies above, Alvarenga et al. (2022) stated that their land-based mining model has higher energy requirements, because the polymetallic nodules in the deep-sea model have a higher ore grade.

Lastly, **Fritz et al. (2023)** reported their land-based system in detail. They assumed open-pit mining for the excavation of the ores. After that, comminution of the ores takes place. Then, three processing routes are followed. These processes were based on the existing Murrin Murrin project (for Ni/Co), Woodie Woodie project (for FeMn), and Kevitsa project (for Cu/Ni/Co). As explained in the detailed final report provided by the authors, these three land-based mines were selected by the BGR because they best match for comparison with the DSM alternative, they are well-established in the market, and they are considered economically viable. The final report showed that the total electricity consumption of the land-based mining model is approximately 884 kWh for producing 9.2 kg of Ni, 7.0 kg of Cu, 1.3 kg of Co and 203 kg of FeMn<sup>1</sup>, which is almost twice as much as that of the deep-sea mining model.

Furthermore, the studies assumed electricity mixes that are dominated by fossil fuels. Benchmark Mineral Intelligence (2022) assumed that the electricity for the conventional land-based alternative comes from the carbon-intensive Australian electricity mix. Fritz et al. (2023) assumed that the electricity for the Woodie Woodie project (FeMn) comes from the Chinese electricity mix, which is dominated by fossil fuels, and the electricity for the Murrin Murrin project (Ni/Co) is generated on-site by burning natural gas and sulfur. However, the electricity for the Kevitsa project (Cu/Ni/Co) comes from the Finnish electricity mix, which is dominated by hydropower. Furthermore, the studies of Paulikas et al. (2020b, 2020a) assumed for their "baseline scenario" that the electricity mix is dominated by fossil fuels, while for the "green scenario" the mix is dominated by renewables. However, none of the studies assumed 100% renewable electricity for the land-based alternative. Paulikas et al. (2020b) further explained that the processing plants for land-based ores are usually close to the mining site in developing countries, and are therefore powered by local electricity mixes that often rely on fossil fuels.

Almost all studies used economic allocation to solve multifunctionality in the land-based system. Similar to the deep-sea mining alternative, the authors argued that this allocation method is commonly used in LCAs about metals. However, Alvarenga et al. (2022) did not report the method they used to address multifunctionality in the land-based system.

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<sup>1</sup>Woodie Woodie = 650 kWh, Murrin Murrin = 113 kWh, Kevitsa = 121 kWh

### 5.2.4. Life-Cycle-Impact Assessment

The LCA studies considered different impact categories to draw conclusions about the environmental sustainability of metals from deep-sea mined polymetallic nodules, compared to land-based mining. The studies of Paulikas et al. (2020a) and Fritz et al. (2023) focused only on the impacts on climate change. However, the LCAs of Alvarenga et al. (2022), Benchmark Mineral Intelligence (2022), and Paulikas et al. (2020b) took into account 3, 21, and 16 impact categories, respectively. All studies considered the impact category "climate change" and used the GWP100 characterization factor method. Furthermore, both Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b) analysed the energy resources impact category. Paulikas et al. (2020b) calculated this category in Petajoule (PJ), whereas Benchmark Mineral Intelligence (2022) used kilograms of oil equivalent (kg oil-eq).

### 5.2.5. Sensitivity Analysis

Almost all studies conducted a sensitivity analysis for the allocation method. Paulikas et al. (2020b, 2020a) conducted a sensitivity analysis in which the results were analysed for using physical allocation instead of economic allocation. This resulted in a significant reduction in emissions for both alternatives, but especially for the DSM alternative. The lower climate change impacts of the nodules compared to land-based ores were robust under both allocation methods. Similarly, Benchmark Mineral Intelligence (2022) conducted a sensitivity analysis applying economic allocation instead of physical allocation to the pyrometallurgical processes, which led to the same conclusion.

Furthermore, Benchmark Mineral Intelligence (2022) and Fritz et al. (2023) performed a sensitivity analysis on the market prices of the metals. These analyses showed that the results are not sensitive to variations in these prices. Benchmark Mineral Intelligence (2022) also conducted a sensitivity analysis on the location of the onshore processing site of the nodules. The authors concluded that the results are not sensitive to variations in this location, because the transshipment to the processing site has a low contribution to the total climate change impacts. Moreover, Fritz et al. (2023) concluded that the climate change results are sensitive to the electricity mix used in both the deep-sea and land-based mining alternatives.

## 5.3. Causes of Differences in Outcomes

In this section, the outcomes and LCA model choices are connected. This aims to explain the differences in outcomes with the differences in how the studies were performed. The previous LCA studies can generally be divided into two groups. The first group consists of the studies by Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b, 2020a), which showed that deep-sea mining is significantly more beneficial in terms of climate change impacts. The other group consists of the studies by Alvarenga et al. (2022) and Fritz et al. (2023), which showed smaller differences between the alternatives. An overview of how these two groups differ is presented in Table 5.5.

**Table 5.5:** Overview of two groups of LCAs that show different outcomes and LCA model choices.

Paulikas et al. (2020b, 2020a) & Benchmark 2022	Alvarenga et al. (2022) & Fritz et al. (2023)
<b>Larger difference</b> in climate change impacts between deep-sea and land-based mining, making deep-sea mining significantly more beneficial.	<b>Smaller difference</b> in climate change impacts between deep-sea and land-based mining, making deep-sea mining less strongly beneficial.
Assume <b>100% renewable electricity</b> for onshore processing of nodules, while assuming electricity mixes dominated by fossil fuels for land-based mining.	Assume electricity mixes with <b>fossil fuels</b> for onshore processing of nodules, while also assuming electricity mixes dominated by fossil fuels for land-based mining.
Assume <b>lower electricity input</b> for onshore processing of the nodules.	Assume <b>higher electricity input</b> for onshore processing of the nodules.
<b>Air lift</b> for vertical transport of nodules.	<b>Hydraulic lift</b> for vertical transport of nodules.
Supported by <b>TMC</b> (private).	Supported by <b>GSR</b> (private) or <b>BGR</b> (public).
Sponsoring state <b>Nauru</b> , which strongly supports deep-sea mining.	Sponsoring states <b>Belgium &amp; Germany</b> , which take a middle-ground position that supports deep-sea mining under strict rules and environmental safeguarding.

As presented in Table 5.5, electricity use for onshore processing is a key explanation for the difference between the three TMC-supported studies and the studies of Alvarenga et al. (2022) and Fritz et al. (2023). All studies agreed that the offshore processes (extraction & vertical transport) contribute relatively little

to the climate change impacts of metals from deep-sea nodules, and that onshore processing is the main contributor. Specifically, the energy-intensive pyrometallurgical processes cause the most impact on climate change. Unlike the other studies, which assumed 100% renewable electricity for onshore processing of the nodules, Alvarenga et al. (2022) and Fritz et al. (2023) assumed electricity mixes with fossil fuels. This resulted in more carbon-intensive pyrometallurgical processing, increasing emissions, and reducing the perceived climate change benefits of deep-sea nodules compared to land-based mining. Alvarenga et al. (2022) also showed that their deep-sea mining scenario with the highest percentage fossil fuels in the mix (Scenario B) resulted in the smallest difference in impact between the nodules and land-based alternatives. Fritz et al. (2023) further demonstrated through a sensitivity analysis that the climate change impacts of both mining alternatives depend highly on the electricity mix used. The other three studies also emphasized that the deep-sea alternative outperforms the land-based alternative in terms of climate change impacts because it consumes less energy and benefits from flexibility in locating the processing plants. They argued that this flexibility allows access to hydropower or other renewable energy sources, which leads to lower climate change impacts. This assumption is especially important since all studies assumed that the land-based mining alternative relies mainly on electricity mixes dominated by fossil fuels.

In addition, Alvarenga et al. (2022) and Fritz et al. (2023) modelled the highest amounts of electricity input for the onshore processing of the polymetallic nodules. This is in line with the observation that these studies concluded a smaller benefit for the deep-sea alternative compared to the land-based alternative in terms of climate change impacts. Scenario A and B of Alvarenga et al. (2022) assumed the same high amount of electricity input for onshore processing. However, Scenario B resulted in a smaller perceived benefit of deep-sea nodules over land-based ores in terms of climate change impacts. This can be explained by the fact that Scenario B assumed the highest percentage of fossil fuels in the mix. This shows that assumptions regarding both energy sources and the amount of energy consumption cause differences in the outcomes about the impacts on climate change.

Conversely, Table 5.5 shows that Alvarenga et al. (2022) and Fritz et al. (2023) assumed a hydraulic lift for vertical transport in the deep-sea alternative, while the other three studies assumed an airlift system. The hydraulic lift is significantly more efficient than the high-energy-consuming airlift (Hu et al., 2022). This is not in line with the broader trend observed in the studies that assumptions regarding energy consumption significantly affect the perceived environmental benefits of deep-sea nodules over land-based ores. This can be explained by the fact that vertical transport of the nodules contributes relatively little to the climate change impacts compared to onshore processing and refining.

Furthermore, the wide variation in the percentage difference for the energy resource scarcity impact category between Benchmark Mineral Intelligence (2022) and Paulikas et al. (2020b) can be explained by their choice of unit. While percentages remain comparable, the units influence how energy consumption is perceived. Petajoules (PJ) measure total energy use, whereas kilograms oil-equivalent (kg oil-eq) represents energy scarcity based on fossil fuel equivalency. Both studies assumed 100% renewable electricity for the energy-intensive onshore processing of the nodules. However, they assumed electricity mixes with fossil fuels for the land-based mining alternative. Therefore, the study that used kilograms oil-equivalent as unit logically resulted in a higher percentage difference, which made the deep-sea nodules alternative significantly more favourable.

#### **5.4. Discussion & Reflection of the LCAs**

First, the LCA studies showed a variation in temporal scope between the alternatives, which complicates the comparability. For example, Alvarenga et al. (2022) modelled land-based mining using data from 2011 to 2013, while their deep-sea mining model is based on more recent data for future production. In addition, since deep-sea mining is expected to take place in the future, it would be reasonable to assume higher shares of renewable energy in the electricity mix. However, to ensure a fair comparison, similar assumptions about increasing renewable energy use should be applied to the land-based mining alternative. Paulikas et al. (2020b, 2020a) addressed this partially by modelling a baseline scenario and a green scenario for land-based mining, but they used only one scenario for deep-sea mining. Applying future renewable energy scenarios to one system, while keeping the other based on current energy mixes, risks overestimating the environmental benefits of deep-sea mining compared to land-based mining.

Furthermore, As explained in Section 5.2.5, Benchmark Mineral Intelligence (2022) performed a sensitivity analysis on the location of the onshore nodule processing site. They concluded that the location does not significantly impact the climate change results, as transshipment to the onshore site contributes relatively little to the overall impacts. However, the locations included in this sensitivity analysis differed only in transshipment distance and had similar energy sources. For the baseline location (Texas) the authors assumed 100% wind energy, for India they assumed captive solar energy with an Energy Storage System, and for Malaysia they assumed 100% hydropower. Therefore, the energy for all locations is assumed to be fully renewable. Although the authors concluded that the results are not sensitive to the location of the onshore processing site, this conclusion could change if the locations differed in electricity source.

Further, Paulikas et al. (2020b) were the only ones that included seabed use (in km<sup>2</sup>) in their analysis. Although the authors kept the land use and seabed use impact categories separate, they argued that the seabed area impacted by deep-sea mining is more than three times as large as the area impacted by land-based mining. As explained in the LCA handbook by Guinée et al. (2002), the land use impact category acknowledges two aspects: transformation and occupation. Transformation is the process of changing parts of the life support functions and biodiversity in the area, measured in square meters (m<sup>2</sup>). Conversely, occupation refers to the time during which the area is not available for other activities, including recovery time. This aspect is measured in square meter-years (m<sup>2</sup> \* year). Since deep-sea mining, in contrast to land-based mining, only occupies the mining area for a short period of time, occupation of the area is low. However, the transformation aspect of land use also applies to the seabed.

Another discussion point lies in the waste and tailings of the two alternatives. Paulikas et al. (2020b, 2020a) assumed that the nodule system in their analysis is a best-practice without any waste or tailings. They considered slag, the main waste stream, to be a useful by-product. Therefore, the study did not include environmental impacts of waste disposal, which were included in the land-based mining system. As a result, for the impact category "solid waste" they concluded 0 Gt for the nodules alternative, which leads to a percentage difference of -100% compared to the land-based alternative. In contrast, Alvarenga et al. (2022) did assume tailings and waste outflows from the SO<sub>2</sub> and refining processes. In addition, Fritz et al. (2023) included waste gypsum, inert waste, and slag as waste outflows in their deep-sea mining system. However, neither Alvarenga et al. (2022) nor Fritz et al. (2023) included the solid waste impact category in their LCA.

Furthermore, most studies excluded sediment plumes from their input and output values in the deep-sea model. Only Benchmark Mineral Intelligence (2022) modelled "mobilised sediment" as an environmental flow. TMC stated that their NORI system uses a return pipe that discharges the return plume at a depth of 1,200 meters (NORI, 2022). However, the potential consequences of the plume on biodiversity and ecosystems are not included in the study by Benchmark Mineral Intelligence (2022).

In addition, Paulikas et al. (2020b) considered the impact category "ore use" in their study. They showed that the amount of ores that is needed for the required metals is significantly higher for land-based ores than for polymetallic nodules. This is because the ore grade, the concentration of the desired metal in the ore, is significantly higher for nodules (Hein et al., 2013). Therefore, producing metals from land-based ores requires more ores and generates more waste and tailings than production from nodules (Paulikas et al., 2020b). Although the other studies did not include this impact category, they did acknowledge the higher ore grade of polymetallic nodules as a reason for the lower energy demand of the deep-sea mining system, as discussed in Section 5.2.3. 5.2.3.

Furthermore, Paulikas et al. (2020b) reported that they included the impact category "SO<sub>x</sub> and NO<sub>x</sub> emissions". However, SO<sub>x</sub> and NO<sub>x</sub> emissions are part of the life cycle inventory and contribute to impact categories rather than being impact categories themselves. These emissions contribute to acidification, eutrophication, and photochemical oxidant formation (Guinée et al., 2002). The authors did include eutrophication in their analysis, but they did not include the other two categories.

# 6

## Aligned Life Cycle Assessment

This chapter presents an aligned LCA study of metals derived from deep-sea polymetallic nodules compared to those from land-based mining. This LCA builds on the comparative analysis described in the previous chapter, as well as recent developments and knowledge in the field. The main focus of this LCA study is a scenario analysis of different electricity sources and the effect of such modelling choices on the results. It should be noted that LCA addresses generic environmental impacts and does not capture impacts on biodiversity and ecosystems, which are particularly critical in the context of deep-sea mining.

### 6.1. Goal & Scope Definition

The objective of this LCA study is to analyse the potential environmental impacts of the production of metals from deep-sea polymetallic nodules compared to land-based ores. The intended application of this research is to inform policy makers, scientists, the industry, the LCA community, and the general public. The gained knowledge aims to contribute to the ongoing discussion regarding deep-sea mining and to help further research in this field.

The study consists of a detailed comparative LCA following a cradle-to-gate approach. Therefore, the life cycle of the metals is considered from the raw material extraction to the refined metal. This excludes the manufacture, use, and disposal of the final metal products. This approach is appropriate for this study as it compares two systems that produce the same metals, which do not differ after production.

Furthermore, attributional LCA (ALCA) methods are used instead of consequential LCA (CLCA) methods. This is most appropriate since ALCA analyses the impact within a system attributed to deliver a specific amount of the functional unit, whereas CLCA considers the impacts within a system in response to changes in the amount of the functional unit (EUCAR, 2020). In addition, the deep-sea mining model is considered prospective (Guinée et al., 2002), because the extraction and processing of deep-sea nodules is not yet in commercial operation.

The geographical scope of the extraction of polymetallic nodules is the CCZ, similar to the five LCA studies discussed in Chapter 5. This area is currently of main interest to deep-sea mining companies (IUCN, 2024). However, for processing the nodules, there are various options and perspectives (Gales, 2023b). While no nodule processing plant has yet been built, it appears feasible to adapt existing facilities with minimal adjustments (The Metals Company, 2025c). Recently, TMC and Pacific Metals Company (PAMCO) successfully demonstrated commercial-scale nodule processing at the PAMCO facility in Hachinohe, Japan (The Metals Company, 2025c). TMC is the first to complete a processing feasibility study, which they used to apply for an exploitation license (The Metals Company, 2025b). Originally, TMC aimed to use this for their ISA exploitation application, but they recently announced that they applied for DSHMRA (USA) permits and licenses instead (The Metals Company, 2025b). In either case, TMC is the first to apply for an exploitation license and is using PAMCO's plant for this purpose. Therefore, this processing route is assumed for the aligned LCA study, making Japan the geographical location for processing the nodules.

In addition, the technological scope of the deep-sea mining alternative is based on the initiative of frontrunner TMC. Accordingly, the collection system follows the NORI project and uses the technology of Allseas (The Metals Company, 2022). The processing technologies are based on the intended processing route in PAMCO's plant, as described above.

On the other hand, the land-based alternative focuses on averages of current mining activities. This product system is based on cobalt, copper, and nickel production from recent Ecoinvent data, as will be explained in Section 6.3.

For the temporal coverage of the study, the desired age of the data is within the last five years, thus from 2020 to 2025. This is considered reasonable since the LCAs described in Chapter 5 also fall within this time range, and the latest version of Ecoinvent is from 2024.

Lastly, this comparative LCA takes a "basket approach", which means that the study is conducted for a group of metals. The metals included in this "basket" are nickel, copper, and cobalt. Since the grade of nodules in the CCZ is estimated to be relatively consistent throughout the area (AMC, 2021), it is assumed that 1 tonne of dry polymetallic nodules from the CCZ consists of 12.10 kg Ni, 9.27 kg Cu, and 1.70 kg Co.<sup>1</sup> This is used to formulate the function, functional unit, alternatives, and reference flows of this study, as presented in Table 6.1.

**Table 6.1:** Function, functional unit, alternatives, and reference flows of the LCA study.

<b>Function</b>	Providing metals (Ni, Cu, Co) to the the market.
<b>Functional Unit</b>	Providing 12.10 kg Ni, 9.27 kg Cu, and 1.70 kg Co to the market.
<b>Alternatives</b>	<i>Alternative 1:</i> Metals from deep-sea mining of polymetallic nodules <i>Alternative 2:</i> Metals from land-based mining
<b>Reference Flows</b>	1) One unit of metals (12.10 kg Ni, 9.27 kg Cu, 1.70 kg Co) from deep-sea mining of polymetallic nodules provided to the market. 2) One unit of metals (12.10 kg Ni, 9.27 kg Cu, 1.70 kg Co) from land-based mining provided to the market.

## 6.2. Flowcharts

The flowchart for the deep-sea mining alternative is presented in Figure 6.1. The grey boxes and blue P-numbers in brackets indicate background processes from the Ecoinvent v3.10.1 cut-off database, while the white boxes represent foreground processes modelled by the researcher. A list of the P-numbers and connecting processes is presented in Appendix C.3. The flowchart follows the same structure as the mining value chain discussed in Chapter 4. The data and assumptions that are used to create the flowchart are detailed in the next subsection and the unit-process table (Appendix C.1). While the flowchart shows all the economic in- and outflows of the foreground processes, the unit-process table also includes the environmental flows. This table is used to model the system in the OpenLCA software.

Furthermore, since the land-based mining system is fully based on Ecoinvent background processes, it does not have a flowchart with new foreground processes. The foreground processes are adapted background processes that are merged into a process that represents the production of 12.10 kg nickel, 9.27 kg copper, and 1.70 kg cobalt from current land-based mining activities. The unit-process table for this can be found in Appendix C.2. As described by Ecoinvent (2025a), the global production of cobalt, nickel, and copper cathode starts with the extraction of the land-based ore through open-cast or underground mining and ends with the refined metal. In addition, intermediate transportation is included, while the usage and end-of-life processes of the metals are excluded. Therefore, the system boundary and included processes are in line with the deep-sea mining alternative.

<sup>1</sup>Assumed is that 1 tonne of dry nodules requires 1.3158 tonnes of wet nodules, since the moisture content of the nodules is estimated to be 24% for the NORI area (Planet Tracker, 2023). 1,120 kt of wet nodules consist of 10.3 kt Ni, 1.45 kt Co, and 7.89 kt Cu (Fritz et al., 2023). So, 1.3158 tonnes of wet nodules consist of 12.10 kg Ni, 9.27 kg Cu, and 1.70 kg Co.

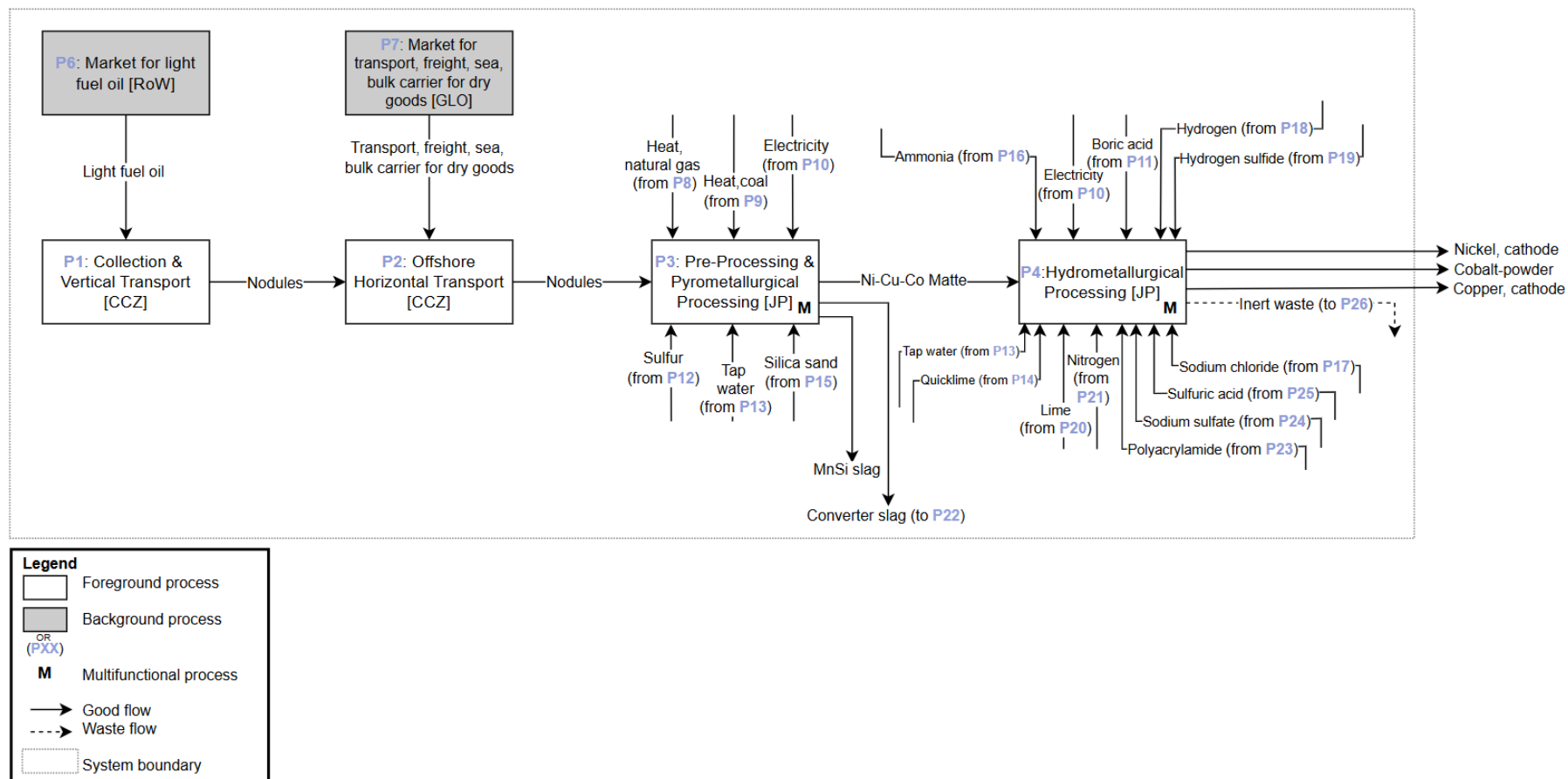


Figure 6.1: Flowchart of the model for deep-sea mining of polymetallic nodules.

### 6.3. Data

The data used in this study are mainly based on the studies of Benchmark Mineral Intelligence (2022) and Fritz et al. (2023) and the Ecoinvent v3.10.1 cut-off database. The data of Benchmark Mineral Intelligence (2022) is used as this study uses project-specific data from TMC's NORI project, which is also the focus of this aligned LCA study. Furthermore, among the studies reviewed in Chapter 5, the study by Fritz et al. (2023) is the most recent, the authors reported their data in most detail, they provided additional information on request, and it is the only study that is not privately funded. Comprehensive details on the data used for the aligned LCA can be found in Appendix C.1, with key considerations summarized below:

- It is assumed that 1 tonne of dry nodules requires 1.32 tonnes of wet nodules, since the moisture content of the nodules is estimated to be 24% for the NORI area (Planet Tracker, 2023; The Metals Company, 2021).
- For the process "Collection & Vertical Transport" data from Benchmark Mineral Intelligence (2022) are used, since this is based on the NORI project of TMC with the collection system of Allseas.
- For the process "Offshore Horizontal Transport", the data of Fritz et al. (2023) are used. However, the transport distance is changed to 10,223 km, corresponding to the distance from the CCZ (NORI-D area) to the port of Hachinohe in Japan (Gales, 2023a).
- There is no onshore horizontal transport modelled in the system, since the processing plant of PAMCO is located directly at the port of Hachinohe, Japan.
- The process "Pre-Processing and Pyrometallurgical Processing" takes place in PAMCO's Rotary Kiln Electric-Arc Furnace (RKEF) facility in Hachinohe, Japan. For this, the data of Benchmark Mineral Intelligence (2022) are used, because their data for pyrometallurgical processing are based on the processing plans of TMC and similar to the processing in the PAMCO plant. This process has as outputs Ni-Cu-Co matte, MnSi slag, and convertor slag.
- The Ni-Cu-Co matte goes into hydrometallurgical processing. The study of Fritz et al. (2023) is used for this, because they modelled further refining of Ni-Cu-Co matte. As stated by Fritz et al. (2023): "Reoxidizing and sulfurizing the Ni-Cu-Co rich forms a matte". So, the processes after this are included, as presented in the red area in Figure 6.2.
- Since there are currently no operating processing plants for these hydrometallurgical processing steps, assumed is that this takes place on the same location as the pre-processing and pyrometallurgical processing. Therefore, in Hachinohe, Japan.
- The electricity for pre-processing, pyrometallurgical processing, and hydrometallurgical processing is assumed to come from the Japanese electricity mix as these processes take place in Japan.
- For the other Ecoinvent background processes, the region Japan was not available. China is assumed to be the most suitable proxy due to its geographical proximity. However, for processes where China was also not available or the data source highlighted a specific region, the selected region is "rest of world" (RoW) or "global" (GLO).
- Fritz et al. (2023) modelled only the outflows of the nodule processing that contribute to climate change. For example, they did not include the emission of water to air. In this aligned LCA study, these flows are included based on their mass-balance.

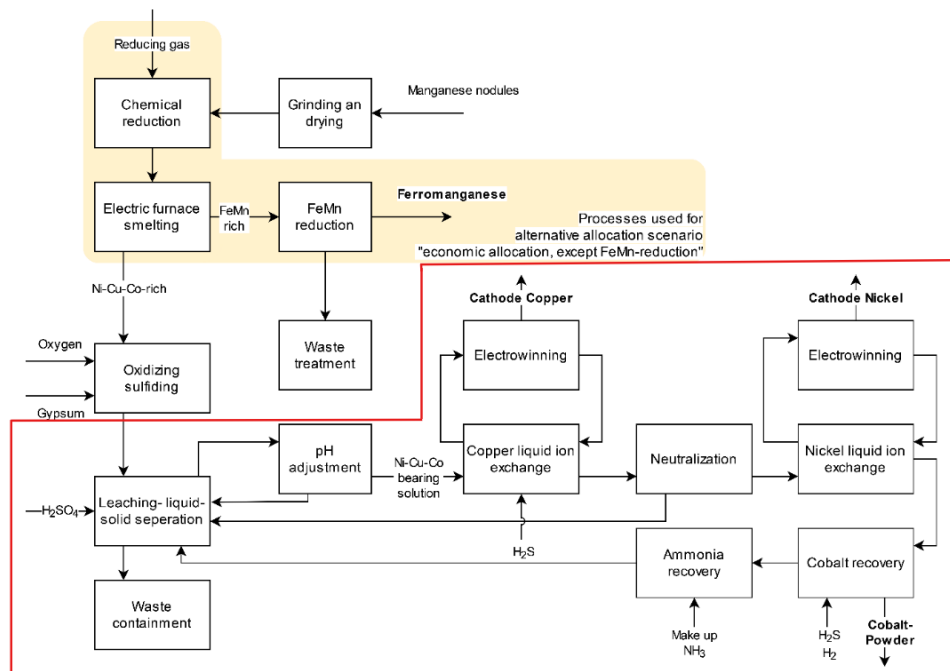


Figure 6.2: Flowchart Fritz et al. (2023) with in red the processes that are assumed to be part of the hydrometallurgical processing.

The land-based mining system is based on the Ecoinvent v3.10.1 cut-off database. In order to compare the land-based system with the deep-sea system, the metal outputs need to be of the same form. As presented in Figure 6.1, for copper, the output is "copper, cathode". This flow can directly be obtained from an Ecoinvent background process that includes the mining and refining of copper cathode. In addition, cobalt is produced in the form "cobalt-powder". Cobalt-powder contains impurities such as oxygen and carbon, but mainly consist of cobalt, with typically a share of 99.8% (Metal 3DP, 2024). Cobalt-powder itself is not available in Ecoinvent, although cobalt production is. Because of the high cobalt content in cobalt-powder, regular cobalt production is assumed for the land-based alternative. Furthermore, in the deep-sea alternative, nickel is modelled in the form "nickel, cathode". This flow corresponds to the "nickel, class 1" flow in Ecoinvent. Class 1 nickel has a higher purity of nickel than class 2 and functions as cathode in batteries (Zeb Nickel Corp, 2025).

The data of USGS (2025) on the global land-based mine production is used to identify the top-producing countries for nickel, copper, and cobalt. For nickel, eight countries were selected with the highest mining production shares that together account for 88 percent of the world's total nickel production from land-based mining. Among these, Indonesia is the largest producer. Ecoinvent has a specific land-based mining process for nickel class 1 production in the Russian Federation, which is used for this country. However, for the other countries, there is no mining process available for nickel from these specific countries. Therefore, the global nickel class 1 background process in Ecoinvent was adapted for each of these countries by adjusting the locations of the background processes of the flows in the process to match those countries. For the flows where the location was not available, the initial global average was used. Appendix C.2 provides an overview of which flows were changed for which location. Then, the nickel production from each of these countries was included based on their percentage production share, relative to each other. Together, this leads to the total nickel production of 12.10 kg.

The same is done for copper and cobalt. The copper cathode production is based on the production of 13 countries that together account for 87 percent of the world's copper mining production. Chile is the largest producer. The cobalt production is based on the production of three countries that together account for 89 percent of the total production. The Democratic Republic of Congo (DRC) is the largest producer of mined cobalt, accounting for 76 percent of the total. However, in contrast to nickel and copper, cobalt is mainly refined outside of the mining countries. China dominates global cobalt refining and the majority of the cobalt that China refines comes from the mines in the DRC and Indonesia. Therefore, China is included as a production location with a share equal to the combined share of the DRC and Indonesia.

## 6.4. Multifunctionality & Allocation

Some processes in the deep-sea mining system yield more than one functional unit and are therefore multifunctional. Multifunctionality occurs when there is co-production, combined waste processing, or recycling. The multifunctional processes in the deep-sea mining system are marked with a capital "M" in Figure 6.1. As shown, "Pre-Processing & Pyrometallurgical Processing" and "Hydrometallurgical Processing" are co-production processes, since they produce more than one output.

Economic allocation is used to solve the multifunctionalities. With this allocation method, inflows and outflows are distributed based on the economic values of the products. This allocation method is chosen because it is considered the norm in LCAs on metal production (Fritz et al., 2023; Paulikas et al., 2020b, 2020a). The current market values of nickel, copper cathode, and cobalt-powder are about \$15.15, \$9.65, and \$31.70 per kg respectively (SMM, 2025a, 2025c, 2025d). However, since this study takes a "basket approach" of the group of metals, allocation between the metals in the "Hydrometallurgical Processing" is not necessary.

The multifunctionality of "Pre-Processing & Pyrometallurgical Processing" is also solved through economic allocation. The market value of the Ni-Cu-Co matte is based on the market values of the three metals as described above and the composition of the metals in the matte. Therefore, the market value of this matte is \$342.40.<sup>2</sup> In addition, the market value of MnSi slag is based on the economic value of SiMn alloy, which is used as an important input in steel production and made of the slag (The Metals Company, 2023b). Therefore, the market value of the MnSi slag is assumed to be \$538.24.<sup>3</sup> Lastly, similar to Benchmark Mineral Intelligence (2022), the converter slag is modelled as an avoided product.

## 6.5. Life-Cycle Inventory Results

The LCI results can be found in Appendix D.1. They present the lists of system-wide environmental flows that are related to the reference flows for both the deep-sea and the land-based mining systems. In other words, they present all the environmental inputs and outputs of the system for producing 12.10 kg Ni, 9.27 kg Cu, and 1.70 kg Co from deep-sea or land-based mining.

Notably, Radon-222 is a major emission to air for both alternatives. However, the emission of this radioactive gas is significantly higher for the land-based alternative. Radon-222 poses a significant threat to human health (Mphaga et al., 2024). Additionally, radioactive noble gases emitted to air are high for both alternatives, but especially for the land-based alternative.

Further noticeable is that both alternatives require a large amount of water for turbines that generate energy. Again, this amount is significantly higher for the land-based alternative.

## 6.6. Life-Cycle Impact Assessment

For the impact assessment, the ReCiPe 2016 v1.03 Midpoint (H) method is selected. This assessment method was developed by the Dutch research institute RIVM, Leiden University, Radboud University Nijmegen, and Pré Consultants (Ecoinvent, 2024). This method is chosen because it includes a wide variety of midpoint impact categories that are relevant for this study, such as climate change and water use. An overview and definitions of these impact categories are provided Appendix A.

The ReCiPe 2016 v1.03 Midpoint (H) has 18 impact categories. These categories represent the environmental issues to which the LCI results are assigned (ISO, 2006). Every category is quantified by a category indicator (ISO, 2006). To convert all emissions related to one impact category to the common unit of the indicator, a characterization factor is used (ISO, 2006). For example, for the impact category climate change, the Global Warming Potential (GWP) is used as the characterization factor (RIVM, 2016).

In the classification step, LCI results are assigned to impact categories. For example, carbon dioxide and methane are assigned to climate change. Some emissions can contribute to multiple categories. The mass values of all emissions in a category are multiplied by their characterization factor to obtain the

<sup>2</sup>For nickel: 12.10 kg nickel cathode comes out of the matte and the market value is \$15.15 per kg (SMM, 2025d).

For copper: 9.27 kg copper cathode comes out of the matte and the market value is \$9.65 per kg (SMM, 2025c)

For cobalt: 1.70 kg cobalt comes out of the matte and the market value is \$31.70 per kg (SMM, 2025a).

Economic value of the matte is  $((12.1/(12.1+1.7+9.27))*15.15+1.7/(12.1+1.7+9.27)*31.7+9.27/(12.1+1.7+9.27)*9.65)*24.18=)$  \$342.40

<sup>3</sup>The market value of MnSi slag is assumed to be about 700 USD/tonne (SMM, 2025b) and the amount of MnSi slag is 768.92 kg. So, the economic value of the MnSi slag is  $(700/1000*768.92=)$  \$538.24

characterized value, expressed in the same unit. This unit is always an equivalent (e.g., kg CO<sub>2</sub>-Eq). These values are then summed to produce the final characterization result for that category. This classification process is automatically performed in the ReCiPe 2016 impact method.

In addition to the 18 impact categories of ReCiPe 2016, the category "Transformation of natural land" is included. As explained in Section 5.4, land use can be divided into occupation (in  $m^2a$ ) and transformation (in  $m^2$ ). The land use category of ReCiPe 2016 only accounts for occupation (RIVM, 2016). Therefore, the direct transformation of natural land (in  $m^2$ ) is added separately. This category is calculated with the life-cycle-inventory results (Appendix B.2), by summing all the resource inflows related to transformation of land, such as transformation of forest, grassland, and seabed. Flows representing transformation of non-natural land, such as industrial areas, are excluded. Similar to Paulikas et al. (2020b), the transformation of the seabed is presented separately in the characterization results due to the nature of this study.

## 6.7. Characterization Results Baseline

The characterization results of the baseline model for producing 12.10 kg Ni, 9.27 kg Cu, and 1.70 kg Co are shown in Table 6.2, with the percentage differences between the alternatives presented in Figure 6.3. A higher characterization value indicates a higher potential environmental impact. The two mining alternatives can be compared for each category. Since the results are based on a model rather than real-world measurements, they should be interpreted comparatively instead of in absolute terms. These results reflect the baseline scenario, while Section 6.8 presents the results for different electricity source scenarios. Furthermore, in the baseline results shown in Table 6.2, the highest value per category is highlighted. The land-based mining alternative has higher potential impacts in most categories, making deep-sea mining more beneficial, except for the transformation of natural land, including the seabed.

**Table 6.2:** Characterization results for producing 12.10 kg Ni, 9.27 kg Cu, and 1.70 kg Co from deep-sea and land-based mining.

Impact Categories	Unit	DSM Alternative	Land-Based Alternative
Acidification: terrestrial	kg SO <sub>2</sub> -Eq	3.08E+00	1.77E+01
Climate change	kg CO <sub>2</sub> -Eq	6.62E+02	2.63E+03
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1.27E+01	1.07E+03
Ecotoxicity: marine	kg 1,4-DCB-Eq	1.70E+01	1.34E+03
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	8.12E+02	1.59E+04
Energy resources	kg oil-Eq	1.59E+02	6.49E+02
Eutrophication: freshwater	kg P-Eq	1.06E-01	4.76E+00
Eutrophication: marine	kg N-Eq	1.22E-02	3.22E-01
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	4.68E+01	4.11E+02
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	3.44E+02	1.41E+04
Ionising radiation	kBq Co-60-Eq	1.65E+01	4.53E+01
Land use (occupation)	m <sup>2</sup> *a crop-Eq	1.11E+01	2.72E+01
Material resources	kg Cu-Eq	3.65E+00	1.50E+02
Ozone depletion	kg CFC-11-Eq	1.10E-04	8.30E-04
Particulate matter formation	kg PM <sub>2,5</sub> -Eq	1.06E+00	4.37E+01
POF: human health	kg NO <sub>x</sub> -Eq	1.76E+00	7.71E+00
POF: terrestrial ecosystems	kg NO <sub>x</sub> -Eq	1.80E+00	7.84E+00
Water use	m <sup>3</sup>	4.50E+00	1.42E+01
Transformation natural land	m <sup>2</sup>	6.48E+01	5.72E-01
Incl. Transformation seabed	m <sup>2</sup>	6.44E+01	2.25E-02

The percentage reduction between the two alternatives is calculated for each impact category. Specifically, for categories where the deep-sea alternative has a lower impact, the percentage reduction of the deep-sea alternative relative to the land-based alternative is reported.<sup>4</sup> Conversely, for categories where the land-based alternative performs better, the percentage reduction of the land-based alternative relative to the deep-sea alternative is calculated.<sup>5</sup> The results are presented in Figure 6.3. The blue bars indicate categories where the deep-sea alternative has lower impacts and is thus more beneficial, while the orange bars indicate categories where the land-based alternative is more beneficial.

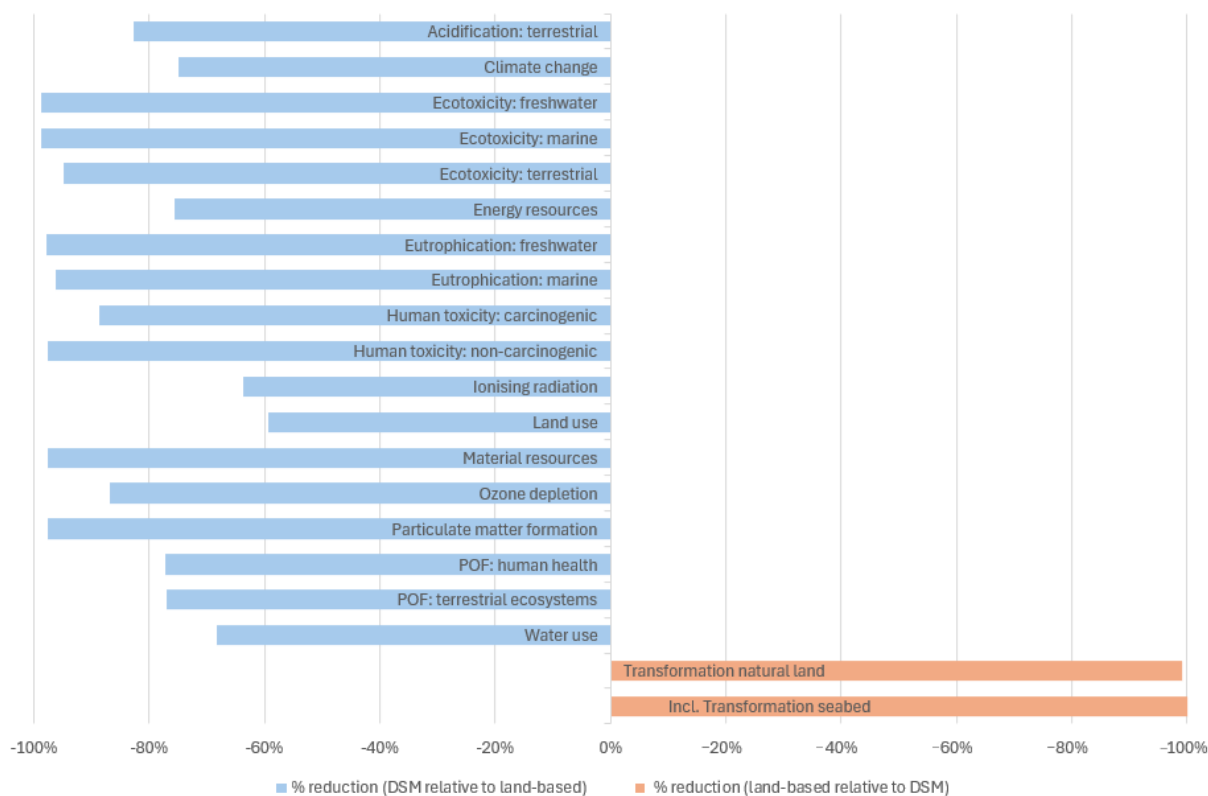


Figure 6.3: Percentage reductions between deep-sea mining and land-based mining.

As shown in the figure, the deep-sea alternative leads to a significant reduction in potential impacts compared to the land-based mining alternative for the following categories: acidification, ecotoxicity, eutrophication, human toxicity, material resources, ozone depletion, and particulate matter formation. In addition, the percentage reduction of the deep-sea alternative relative to the land-based alternative for climate change and energy resources are 75% and 76%, respectively. The deep-sea alternative also shows potential benefits for ionising radiation, land use, and water use. For these categories the reduction percentages are below 70%.

Conversely, the land-based alternative shows a significant reduction in potential impacts for the transformation of natural land, including the transformation of seabed. The transformation of the seabed in the deep-sea mining alternative is so substantial that it exceeds even the total transformation of natural land in the land-based alternative (see Figure 6.2).

4

$$\% \text{ reduction DSM relative to land-based} = \frac{\text{impact value of DSM alternative} - \text{impact value of land-based alternative}}{\text{impact value of land-based alternative}} \times 100\%$$

5

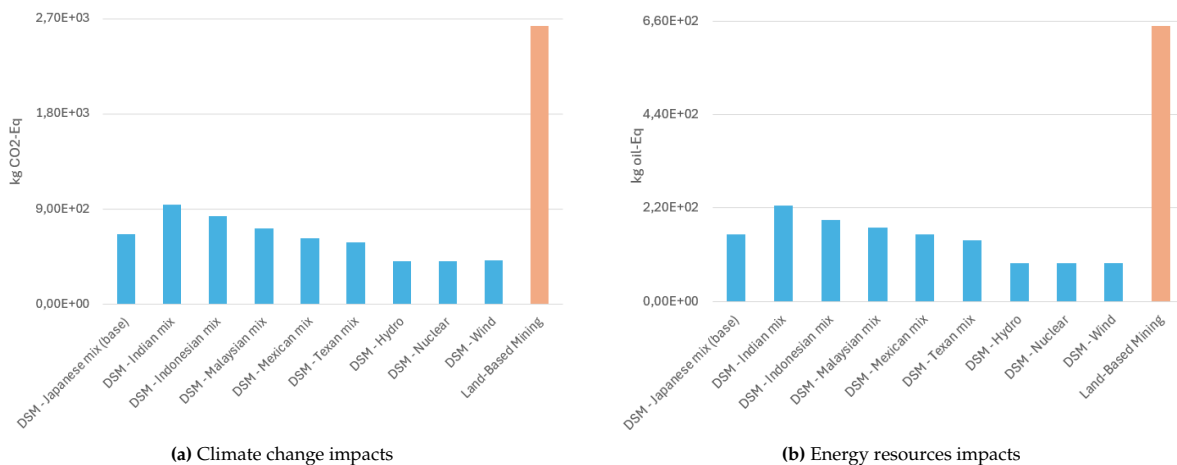
$$\% \text{ reduction land-based relative to DSM} = \frac{\text{impact value of land-based alternative} - \text{impact value of DSM alternative}}{\text{impact value of DSM alternative}} \times 100\%$$

## 6.8. Results Scenario Analysis Electricity Sources

As discussed in Chapter 5, the choice of electricity source can significantly affect climate change impacts, and since offshore nodule processing allows flexible electricity sourcing, several scenarios are analysed. These scenarios assume fixed electricity consumption in the foreground processes, which is 660 kWh<sup>6</sup> for deep-sea mining and 2594 kWh<sup>7</sup> for land-based mining. Section 6.10.5 presents a sensitivity analysis on the amount of electricity input for processing the nodules. This current section first presents the results for various electricity sources used in nodule processing against the baseline land-based mining model. Subsequently, the reverse is examined: the effect of applying different electricity sources to the land-based model, compared to the baseline scenario for deep-sea mining.

### 6.8.1. Electricity Source Processing Nodules

For this scenario analysis, the results are calculated for the following electricity sources for processing the nodules in the deep-sea mining model: the Japanese electricity mix (base), the Mexican electricity mix, the Indian mix, the Malaysian mix, the Texan mix, the Indonesian mix, 100% wind energy, 100% hydropower, and 100% nuclear energy. The Mexican mix is included since several studies described in Chapter 5 assumed Mexico as the processing location. Benchmark Mineral Intelligence (2022) also reported India (Gopalpur), Malaysia (Sarawak), and Texas as possible processing locations for TMC. In addition, a potential nodule processing facility is located in the Indonesia Morowali Industrial Park (IMIP) (Gales, 2023a), making the Indonesian electricity mix a relevant electricity source. In addition to these electricity mixes, different renewable energy sources are included, as several previous LCA studies (Chapter 5) assumed 100% renewables for processing. The results of this scenario analysis (Appendix D.3.1) indicate that some impact categories strongly depend on the electricity source. Figure 6.4 shows the impact values for the climate change and energy resources categories for deep-sea mining (blue) with different electricity sources and for land-based mining (orange).



**Figure 6.4:** Impact values of the deep-sea alternative with different electricity sources and the land-based mining alternative.

The figure shows that the land-based mining alternative has substantially higher impacts on climate change and energy resources than the deep-sea alternative, even when different electricity sources are used for nodule processing. However, as will be discussed in Section 6.8.2, the impacts of the deep-sea alternative can exceed those of the land-based alternative if different electricity sources are applied to the land-based model. It is important to note that the land-based mining model consumes significantly more electricity (2594 kWh compared to 660 kWh), making its results more sensitive to changes in the electricity source.

Furthermore, Figure 6.4a shows that the climate change impacts of the deep-sea alternative are relatively high for the production mixes, especially for the Indian mix. In addition, the graph shows that when the deep-sea alternative uses renewable energy sources (wind, hydro or nuclear), the climate change impacts of this alternative are relatively low, making the deep-sea alternative even more beneficial. The same pattern occurs for the energy resources impact category (Figure 6.4b).

<sup>6</sup>Pre- & pyro processing = 460 kWh, Hydro processing = 200 kWh

<sup>7</sup>Cobalt production = 625 kWh, Copper production = 74 kWh, Nickel = 1895 kWh.

In addition, the impacts on water use and ionising radiation also vary for different electricity sources used for processing the nodules. As presented in Figure 6.5a, the water use of the deep-sea alternative exceeds the land-based alternative when hydropower is applied. In addition, Figure 6.5b shows that the deep-sea alternative becomes significantly less beneficial in terms of ionising radiation impacts when nuclear power is used. In this case, the percentage reduction of the land-based alternative relative to the deep-sea alternative is 83%. In the baseline model, using the Japanese electricity mix, the deep-sea alternative reduces impacts by 64% compared to land-based mining. Therefore, the results depend heavily on the model choices with respect to the electricity source.

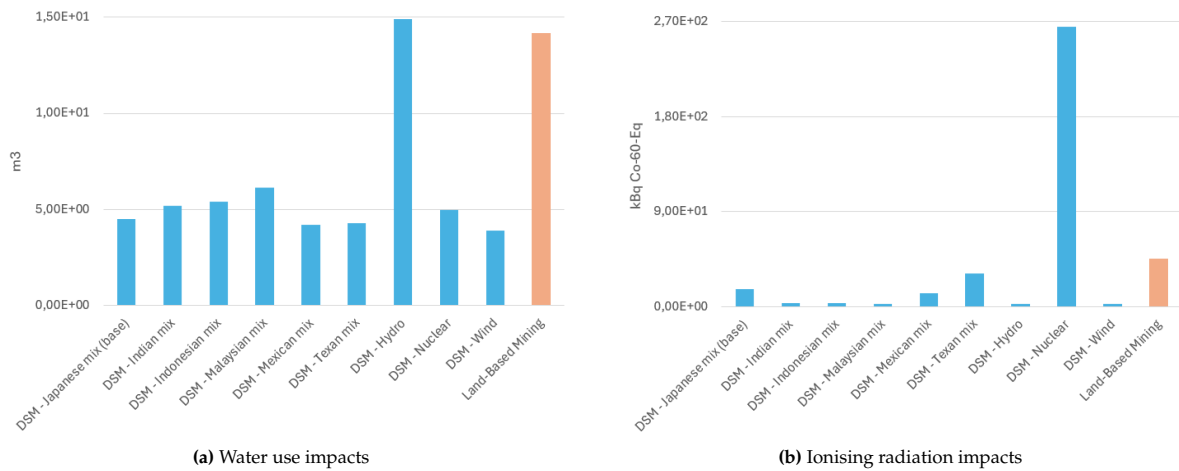


Figure 6.5: Impact values of the deep-sea alternative with different electricity sources and the land-based mining alternative.

### 6.8.2. Electricity Source Land-Based Mining

In the baseline model, land-based mining uses electricity mixes reflecting the top-producing countries for nickel, copper, and cobalt, as described in Section 6.3. In this analysis, scenarios are evaluated where electricity is sourced exclusively from each of these countries individually: Chile, China, DRC, Indonesia, the Philippines, and the Russian Federation. Additionally, Norway and Paraguay are included, because these countries have electricity mixes that are almost entirely based on renewable energy, specifically hydropower (Bindman, 2023; IEA, 2022). Denmark is also included, as this country has the highest share of wind energy in its mix (WindEurope, 2024). In contrast, China, Indonesia, and the Philippines have carbon-intensive electricity mixes (Ember, 2025a), but these locations are already included as alternative electricity sources in this scenario analysis. The results of this analysis (Appendix D.3.2) show that the LCA outcomes depend strongly on the choice of electricity source in the land-based system. Figure 6.6 compares the climate change and energy resource impacts of the land-based alternative under these different electricity scenarios (orange) with those of the baseline deep-sea alternative (blue).

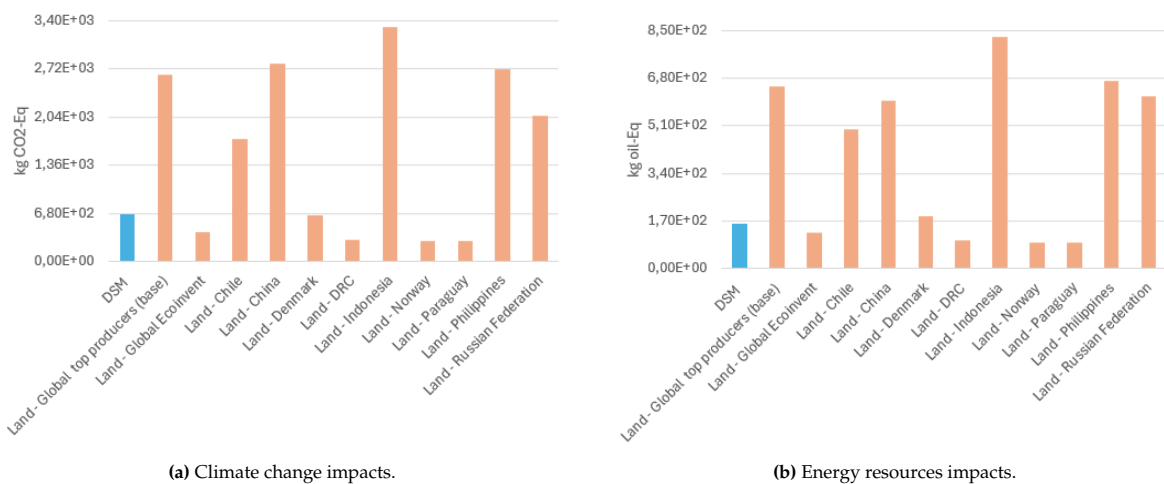
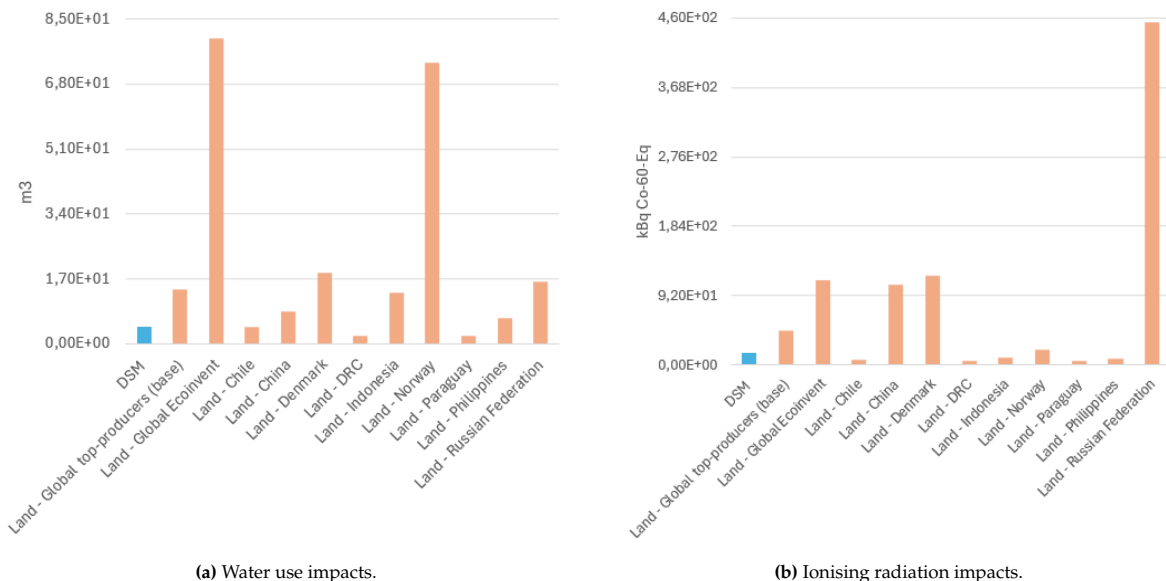


Figure 6.6: Impact values of the deep-sea alternative and the land-based alternative with different electricity sources.

The figure shows that when electricity for metal production in land-based mining is sourced from Indonesia, the impacts on climate change and energy resources are the highest. Consequently, the percentage difference between the land-based and deep-sea alternative is greatest for this electricity source, making the deep-sea alternative significantly more advantageous. In the initial land-based mining model, the electricity source is based on the global top-producing countries of nickel, copper, and cobalt. Indonesia is the largest global nickel producer and accounts for 68% of the nickel production in the land-based model. In addition, nickel production is the largest contributor to the climate change and energy resources impact categories (Section 6.9.1). Therefore, the impacts of the initial electricity source from the global top-producing countries are also substantially higher compared to deep-sea mining. Furthermore, Figure 6.6 shows that the Chilean, Chinese, Philippine, and Russian electricity mixes also lead to relatively large climate change and energy resources impacts.

Conversely, when electricity from Denmark, DRC, Norway, Paraguay, or the global averages of Ecoinvent are used, the impacts of the land-based mining alternative are relatively low. This even leads to lower impacts than the deep-sea mining alternative, making land-based mining more beneficial. The percentage reductions of land-based mining relative to deep-sea mining are 3%, 53%, 55%, 57%, and 47% for Denmark, DRC, Norway, Paraguay, and Ecoinvent's global average, respectively. Therefore, land-based mining is most beneficial in terms of climate change and energy resources when the Paraguayan electricity mix is applied in this system.

The Paraguayan mix, Norwegian mix, and Ecoinvent's global average production have in common that they are all highly based on hydropower (Bindman, 2023; Ecoinvent, 2025b; IEA, 2022). For Norway and the global electricity production this also leads to high water use, as presented in Figure 6.7a. Further, Figure 6.7b shows the impact values on ionising radiation of the land-based alternative (orange) when the different electricity sources are applied, in comparison with the deep-sea mining alternative (blue)



**Figure 6.7:** Impact values of the deep-sea alternative and the land-based mining alternative with different electricity sources for nickel production for the categories (a) Water use and (b) Ionising radiation

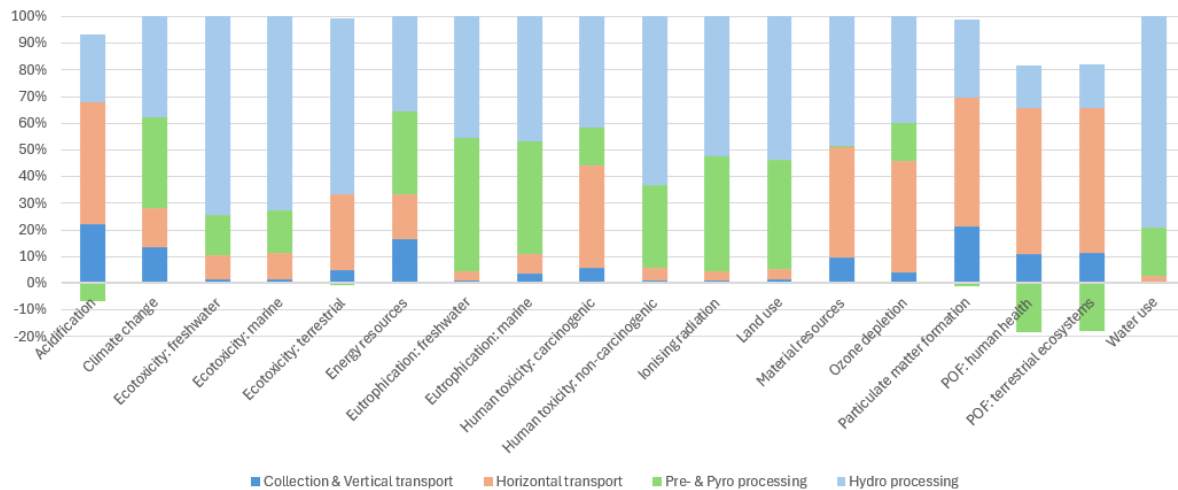
As presented in Figure 6.7b, the ionising radiation impacts of the land-based alternative increase substantially when the electricity from the Russian Federation is used. This makes the land-based alternative remarkably less beneficial than deep-sea mining. Conversely, when electricity is sourced from Chile, DRC, Indonesia, Paraguay, or the Philippines, the impacts become so low that they outperform the deep-sea mining alternative.

## 6.9. Contribution Analysis

Contribution analyses determine the contribution of phases, processes, or flows to the impacts (Guinée et al., 2002). This section captures the contribution of the phases and processes in the baseline system.

### 6.9.1. Phase Contribution

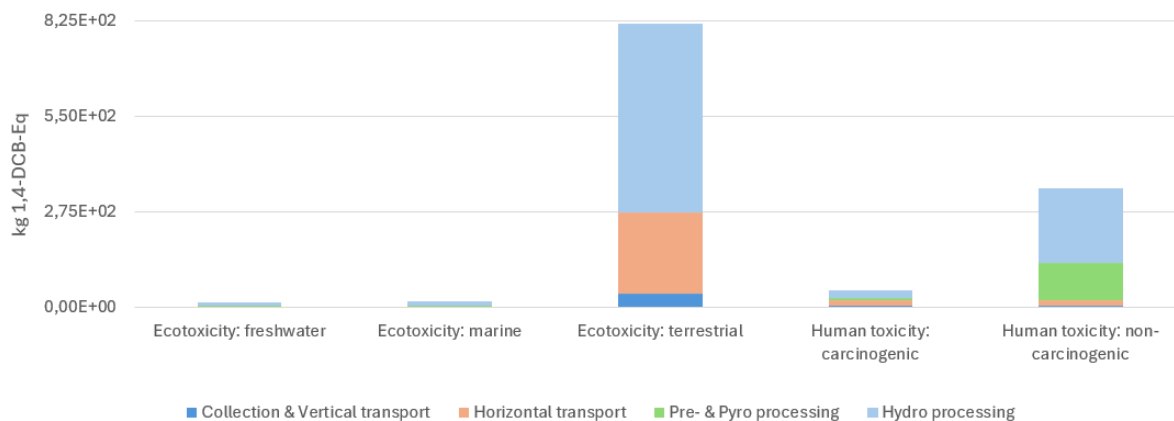
The deep-sea mining system includes four phases: 1) Collection & vertical transport 2) Horizontal transport 3) Pre- & pyrometallurgical processing 4) Hydrometallurgical processing. Figure 6.8 presents the percentage contribution of these four phases to the ReCiPe 2016 impact categories.



**Figure 6.8:** Contribution of the phases in the deep-sea system to the ReCiPe impact categories, with positive percentages presenting phases that add to the impacts and negative percentages presenting phases that reduce the impacts.

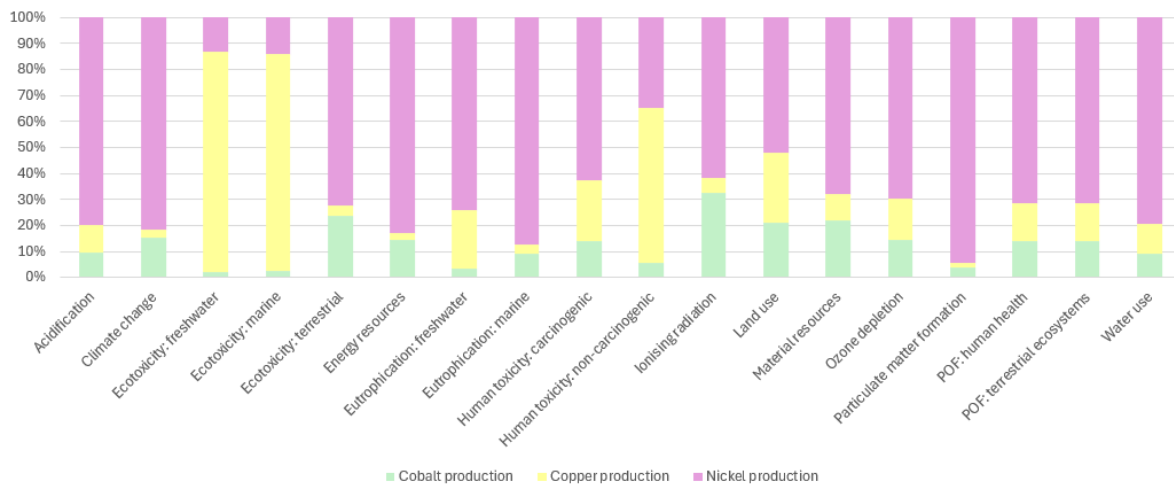
The figure shows that nodule processing contributes most to the impacts in nearly all categories. For instance, the two processing phases account for 72% of the climate change impacts, while collection & vertical transport contribute only 13%. In contrast, horizontal transport is the main contributor to acidification, particulate matter formation, and POF. Furthermore, pre- and pyrometallurgical processing has a negative contribution to acidification and POF. This can be explained by the converter slag modelled as an avoided product and recycling processes in upstream background processes.

Furthermore, small variations can be observed across the five toxicity impact categories. The hydrometallurgical processing phase remains the largest contributor to these impacts. However, horizontal transport contributes proportionally more to terrestrial ecotoxicity than to freshwater and marine ecotoxicity, highlighting that emissions during transport more strongly affect land-based ecosystems. Similarly, horizontal transport contributes relatively more to carcinogenic human toxicity than to non-carcinogenic toxicity, indicating the release of substances that specifically increase carcinogenic risk. Figure 6.9 illustrates the contribution of each phase to the absolute toxicity impacts expressed in kg 1,4-DCB-Eq. The figure shows that terrestrial ecotoxicity, with its higher contribution from horizontal transport, also has a significant larger absolute impact value than the other toxicity categories.



**Figure 6.9:** Contribution of the phases to the absolute toxicity impacts in the deep-sea mining system.

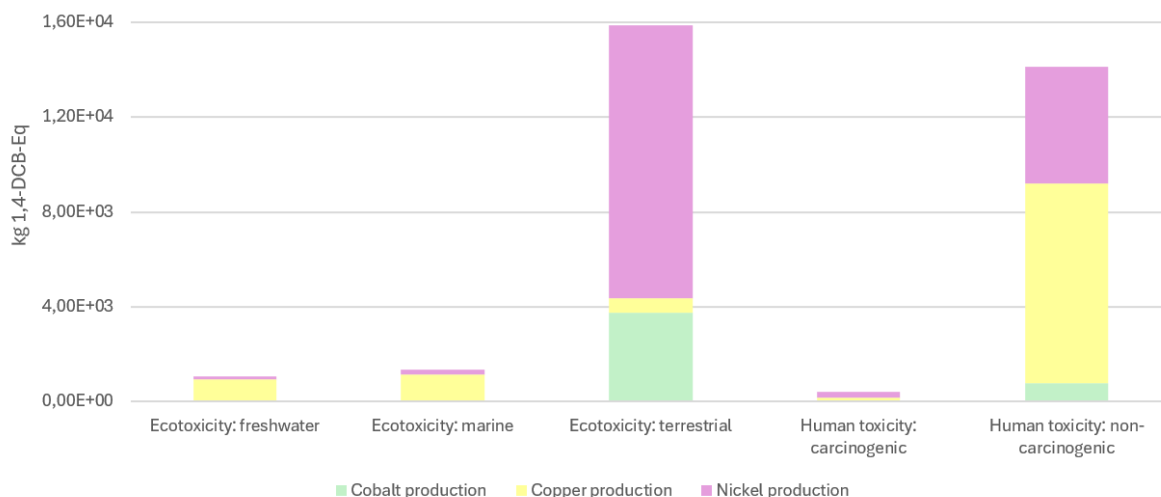
Furthermore, the land-based mining system can be divided into the production of nickel, copper, and cobalt. The percentage contribution of these production paths is shown in Figure 6.10.



**Figure 6.10:** Contribution of the production of the three metals in the land-based mining system to the ReCiPe impact categories.

Figure 6.10 shows that nickel production is the main contributor to most impact categories. For example, 82% of the climate change impacts are caused by the production of nickel. This metal also has the largest share by mass in the metals “basket” analysed in this study. However, the figure also reveals that copper production dominates freshwater and marine ecotoxicity, as well as non-carcinogenic human toxicity. As will be explained in Section 6.9.2, waste treatment processes contribute most to these impacts. Therefore, the reason that copper production is the main cause of these impacts is the sulphidic tailings of copper production. As further explained in Section 6.11.5, treatment of sulphidic tailings causes these toxicity-impacts.

Figure 6.11 presents the absolute values of the five toxicity impact categories, expressed in kg 1,4-DCB-Eq. Similar to the deep-sea mining model (see Figure 6.9), terrestrial ecotoxicity and non-carcinogenic human toxicity impacts are significantly higher than the other toxicity categories. Therefore, while Figure 6.10 shows that freshwater and marine ecotoxicity impacts are dominated by copper production, Figure 6.11 reveals that the absolute impacts of these categories are relatively low compared to the other toxicity categories. In contrast, non-carcinogenic human toxicity impacts are relatively high, indicating a strong influence from copper production.



**Figure 6.11:** Contribution of the production of the three metals to the absolute toxicity impacts in the land-based mining system.

Furthermore, Figure 6.12 presents the phase contributions of both mining alternatives in terms of absolute impact values for climate change and water use. It shows that the absolute impacts of land-based mining are significantly higher than those of deep-sea mining. Notably, the impacts from nickel production alone exceeds the total impacts of the deep-sea mining alternative. Specifically for climate change, the impacts from nickel production alone are more than three times greater than the overall impacts of deep-sea mining.

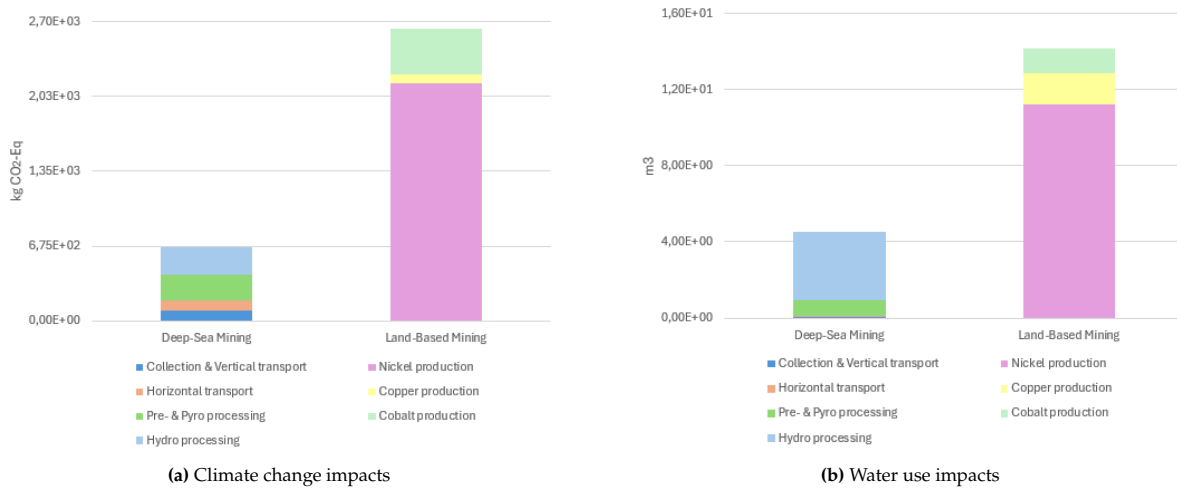


Figure 6.12: Phase contribution to the absolute climate change and water use impacts of deep-sea mining and land-based mining.

For other impact categories, such as particulate matter formation, the difference between the land-based and deep-sea mining alternatives is even larger (see Figure 6.3). Consequently, the contributions of the individual phases within the deep-sea mining model become negligible compared to the substantially higher impacts of land-based mining.

Lastly, Figure 6.13 presents the phase contribution to the electricity consumption, expressed in kWh. This includes the electricity input in the foreground processes of both models, but excludes electricity consumed by upstream background processes. The figure shows that the energy-intensive pre- and pyrometallurgical processing of the nodules consumes the most electricity. It also highlights again that nickel production alone exceeds the total electricity consumption by almost three times. The significantly higher electricity consumption of land-based mining is due to the lower ore grades compared to polymetallic nodules, which increases energy demand. Section 6.10.5 involves a sensitivity analysis on the electricity consumption of the deep-sea mining alternative.

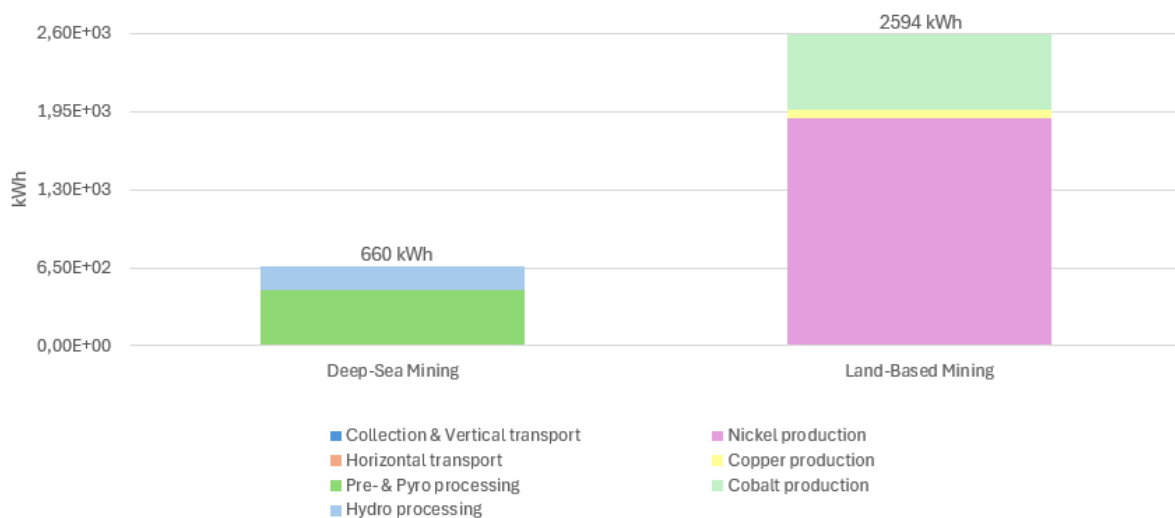
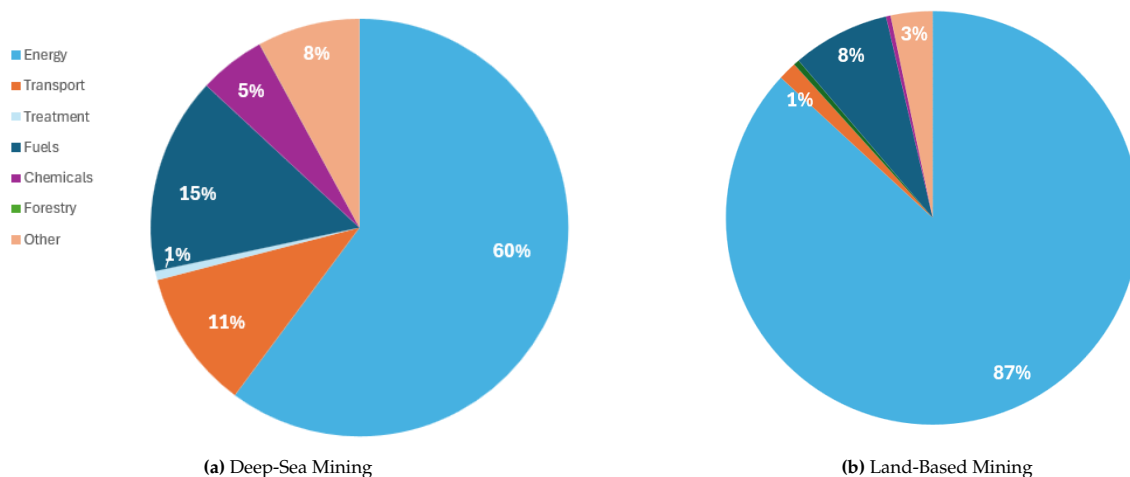


Figure 6.13: Electricity consumption [kWh] of the phases in the deep-sea and land-based mining alternatives.

### 6.9.2. Process Contribution

The contribution of the processes to the impact values of both alternatives is analysed by grouping them into specific categories: energy, transport, treatment, fuels, chemicals, forestry, and other. These groups are formed based on keywords in their process names. For example, the "energy" group includes all the processes with "electricity" or "heat" in its name, such as electricity production processes. These processes are excluded from the remaining groups. For example, the "fuels" group covers the production of hard coal, but excludes the electricity production generated from hard coal. The results are presented in Appendix E.2. The "other" group is relatively large for some categories of the land-based mining system, because these impacts are mainly caused by the specific Ecoinvent processes for producing nickel class 1, copper cathode or cobalt-powder, rather than upstream processes that fall under the groups defined above.

For some impact categories the deep-sea and land-based mining alternatives show similar results. For example, the process group "treatment", which covers the treatment of waste streams, is the main contributor to the following impact categories in both alternatives: freshwater and marine ecotoxicity, freshwater and marine eutrophication, human toxicity, and ionising radiation. In addition, the "fuels" process group logically contributes most to the energy resources category. Additionally, as presented in Figure 6.14, the energy processes account for the largest share of the climate change impacts in both systems.



**Figure 6.14:** Process contribution to the climate change impacts for a) deep-sea mining and b) land-based mining.

The figure shows that the percentage contribution of the energy processes is higher for land-based mining (87%) than for deep-sea mining (60%). This corresponds to the substantially greater electricity use from land-based mining (2594 kWh) compared to deep-sea mining (660 kWh).

Furthermore, the contribution analysis results of the land-based mining system show that energy processes contribute most to the impacts on water use. For this system, 79 percent of all the water use is caused by energy processes. In the deep-sea system, the foreground process "Hydrometallurgical Processing" is the main contributor to the water use impact category (89%). This is expected, as hydrometallurgical processing is water-based processing.

## 6.10. Sensitivity Analysis

Sensitivity analyses are conducted to verify if the obtained information is relevant and reliable to draw conclusions (ISO, 2006). This study includes five sensitivity analyses examining: the allocation method, the market values applied, the chosen impact assessment method, the distance of horizontal transport, and the electricity input used in the deep-sea mining model.

### 6.10.1. Allocation Method

The choice of a specific allocation method, to address multifunctionality, can lead to different results. Therefore, this sensitivity analysis examines the effect of using alternative allocation methods. In the baseline model, the multifunctional process "Pre-Processing & Pyrometallurgical Processing" in the deep-sea nodules system was solved using economic allocation. For this sensitivity analysis, this is replaced with physical allocation, meaning that all non-functional flows are allocated to the functional flows based on their weight percentage. Appendix F.1 presents the characterization results when physical allocation is applied. As the allocation method is changed only for the deep-sea system, the land-based system remains unchanged. The characterization results of the deep-sea nodule alternative decrease significantly. Therefore, the deep-sea alternative becomes even more beneficial across the ReCiPe impact categories. For instance, the reduction in ionising radiation impacts compared to the land-based alternative increases from 64% under economic allocation to 80% under physical allocation. These findings show that the results are sensitive to the choice of allocation method.

This sensitivity can be explained by the characteristics of the final products in the metal "basket". The functional metals considered in the "basket" are nickel, copper, and cobalt, whereas manganese is not included. In the original economic allocation, the higher market values of the metals in the matte compared to the MnSi led to a higher share of the environmental burden being attributed to the functional metals. In contrast, under physical allocation, the environmental impacts are distributed based on mass, meaning that the much larger mass of MnSi receives a proportionally higher share of the burdens. As a result, the Ni-Cu-Co matte carries a lower environmental load under physical allocation, leading to a notable reduction in the overall impacts attributed to the deep-sea mining system. This shift demonstrates that the choice of allocation method can have a substantial influence on comparative LCA results, especially in a system where co-products differ significantly in both mass and economic value.

### 6.10.2. Market Values

The current market values of cobalt, nickel cathode, copper cathode, and SiMn alloy were used for the economic allocation of the multifunctional process "Pre-Processing & Pyrometallurgical Processing". These market values present recent market values and are sourced from SMM (2025a, 2025b, 2025c, 2025d). As discussed in Section 6.4, the market values of nickel, copper cathode, and cobalt-powder are about \$15.15, \$9.65, and \$31.70 per kg, respectively (SMM, 2025a, 2025c, 2025d). For this sensitivity analysis, the market prices are sourced from Ecoinvent (2025a) instead. Ecoinvent (2025a) calculated the prices for cobalt, nickel cathode, and copper cathode from the market averages between 2015 and 2019 and converted this to EURO2005. The market values for nickel class 1, copper cathode, and cobalt are about €12.1, €3.57, and €26.5 per kg, respectively (Ecoinvent, 2025a). These values and the amount of kg of the metals in the Ni-Cu-Co matte is used to calculate the economic value of the matte. As presented in Appendix F.2, this economic value becomes \$407.80 (instead of \$342.4). Since Ecoinvent lacks a market value for MnSi, the original market value is retained. Consequently, this sensitivity analysis focuses on the market values of cobalt, nickel cathode, and copper cathode.

The results of this sensitivity analysis show that using the 5-year average market values from Ecoinvent makes the outcomes of the LCA study slightly more favourable for the land-based alternative. However, the percentage difference between the alternatives change relatively little. For example, the percentage reduction in climate change impacts of the land-based alternative relative to the deep-sea alternative becomes 73%, compared to 75% when using the current SMM market values. This indicates that the results are not particularly sensitive to changes in the market values of cobalt, nickel cathode, and copper cathode. This finding is similar to the outcomes of the sensitivity analyses conducted by the studies described in Chapter 5.

### 6.10.3. Impact Assessment Method

Different impact assessment methods can also lead to different results. Initially, the ReCiPe 2016 method was used. For this sensitivity analysis, the EF v3.1 method is applied. This method was developed by the European Commission and contains several midpoint impact categories (Ecoinvent, 2024). The results of this sensitivity analysis (Appendix F.3) show that the deep-sea alternative still has lower impact values for most categories, with similar percentage reductions. For example, the reduction in climate change impacts of the deep-sea alternative relative to the land-based alternative remains 75%, consistent with the ReCiPe results. However, when applying the EF v3.1 method, the land-based alternative scores a lower impact on the category "human toxicity: carcinogenic, organics". This was not the case when the ReCiPe method was used. However, ReCiPe did not distinguish between inorganic and organic, and the two methods used different units for the human toxicity categories. Further noticeable is that the impact values are slightly higher for all categories when applying EF v3.1 instead of ReCiPe. However, this is the case for both the deep-sea and land-based alternative. Therefore, the difference between the two alternatives remains approximately the same when the EF method is applied instead of ReCiPe.

Furthermore, the CML v4.8 impact assessment method is applied instead of ReCiPe 2016. The CML method was developed by the Institute of Environmental Sciences of the University of Leiden (CML) and contains 11 midpoint impact categories (Ecoinvent, 2024). The results using CML are also similar to those obtained with ReCiPe. The deep-sea alternative is again more beneficial and the percentage reductions are similar to ReCiPe. Therefore, it can be concluded that there are no significant differences in outcomes between these method. However, it should be noted that the CML method includes fewer categories than ReCiPe and some categories are calculated in different units.

### 6.10.4. Distance Horizontal Transport

Benchmark Mineral Intelligence (2022) conducted a sensitivity analysis in their LCA study on the location of the onshore processing of the nodules. As argued in Section 5.4, the locations included in this sensitivity analysis only differed in terms of the distance of the horizontal transport, while they all used renewable energy sources. Therefore, in this aligned LCA study, the influence of different electricity sources is addressed separately in the scenario analysis (see Section 6.8.1), while the impact of different horizontal transport distances is captured in this sensitivity analysis.

As explained in Section 6.8.1, Mexico, India, Malaysia, Texas, and Indonesia are possible alternative locations for processing the nodules in the deep-sea system, instead of Japan. The distances from the CCZ (NORI-D area) to these locations are as follows: 10,223 km (Japan), 1,930 km (Mexico), 19,524 km (India), 15,450 km (Malaysia), 8,751 km (Texas), and 13,455 km (Indonesia) (Benchmark Mineral Intelligence, 2022; Fritz et al., 2023; Gales, 2023a). Figure 6.15 presents the geographic locations of the different processing sites. The outcomes of this sensitivity analysis are presented in Appendix F.4.

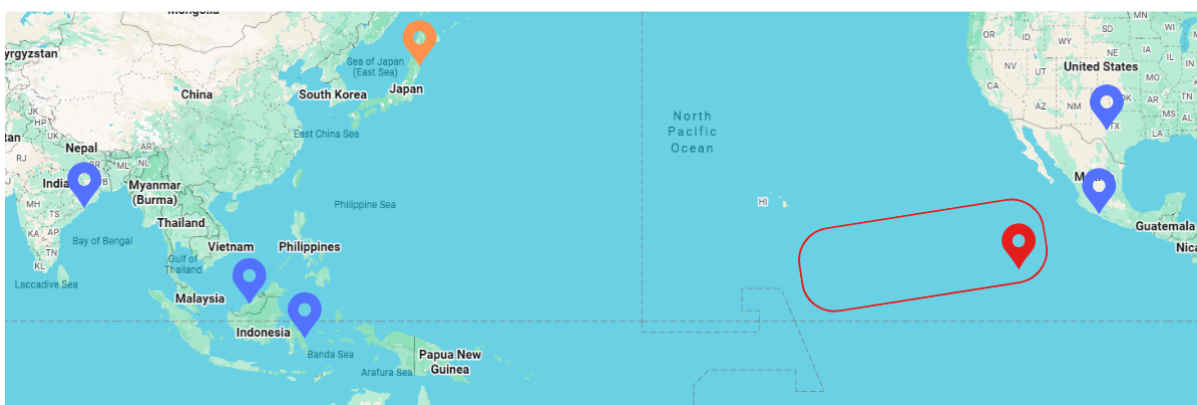
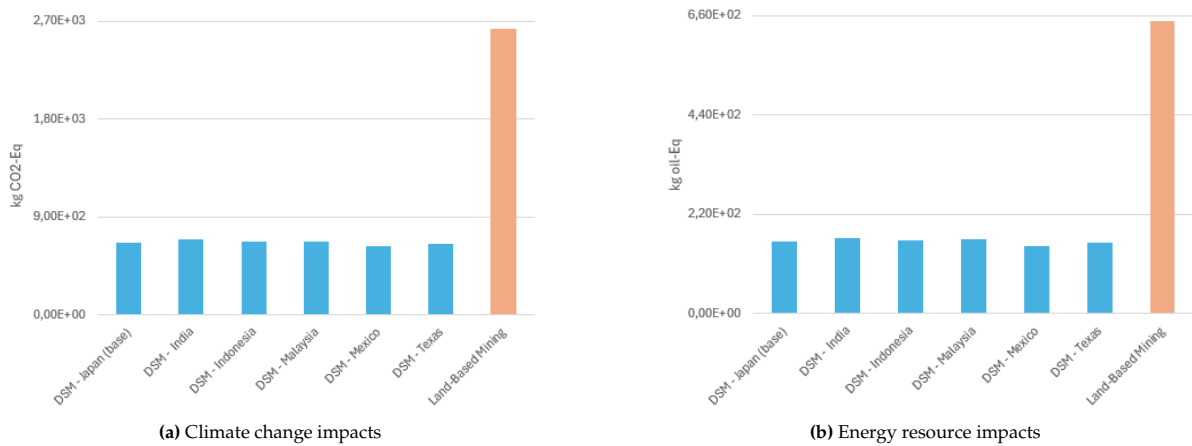


Figure 6.15: Locations of the alternative processing sites (blue), the base processing site (orange), and the extraction site (red), based on Google Maps and Gales (2023a).

The outcomes indicate that the results of the LCA study are not sensitive to variations in the distance of horizontal transport. Specifically, for the climate change and energy resources impact categories, the deep-sea alternative shows approximately the same impact values across the different transport distances. This is illustrated in Figure 6.16.



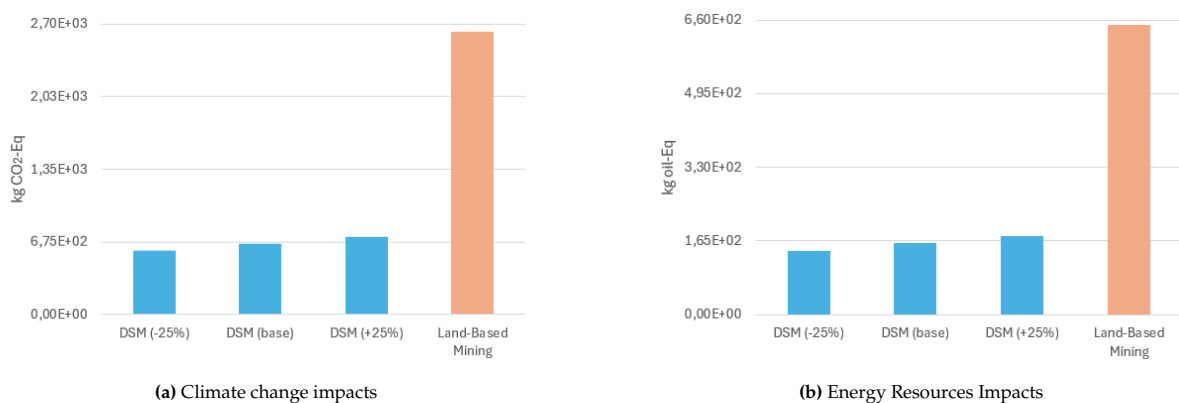
**Figure 6.16:** Impact values of the deep-sea alternative with different horizontal transport distances.

For all impact categories, the impacts of the deep-sea alternative are the lowest when the distance to Mexico is applied. This is because the distance from the extraction site to Mexico is significantly shorter than to the other processing locations. However, as also presented in Figure 6.16, the difference with the other locations is low and the impacts of the land-based alternative remain significantly higher.

### 6.10.5. Electricity Consumption Deep-Sea Mining

As discussed in Chapter 5, electricity consumption significantly influences the climate change impacts. The influence of different electricity sources has already been explored in the scenario analysis in Section 6.8. While the choice of electricity source is flexible, the amount of electricity consumed in the deep-sea mining system is not a matter of choice but is subject to uncertainty, as it depends on the actual ore characteristics and operational efficiency. Therefore, this sensitivity analysis examines whether changes in electricity consumption influence the results by varying the electricity input by  $\pm 25\%$ . It is important to note that this analysis excludes electricity consumed by upstream background processes.

The results of this sensitivity analysis show that none of the impact categories are sensitive to this variation in electricity input. Logically, applying a 25% reduction leads to lower impacts, resulting in a larger difference compared to land-based mining. In contrast, when the electricity input is increased with 25%, the difference with land-based mining becomes smaller. However, as also shown in Figure 6.17, this leads to minor relative changes.



**Figure 6.17:** Impacts for DSM with  $\pm 25\%$  variation in electricity consumption, compared to land-based mining.

The figure shows that even when the electricity consumption of the deep-sea mining model is increased by 25%, the electricity consumption of the land-based mining system remains substantially higher. Specifically, with a 25% increase in electricity input for the deep-sea model, the land-based system still requires more than three times as much electricity.<sup>8</sup> As previously discussed, this higher electricity requirement in land-based mining is primarily driven by the lower ore grades compared to polymetallic nodules. Additionally, it is important to note that this sensitivity analysis uses the baseline electricity mixes, where land-based mining relies largely on carbon-intensive sources (see Section 6.8).

<sup>8</sup> $(2594.18 \text{ kWh}) / (660.25 \times 1.25 \text{ kWh}) = 3.14$

## 6.11. Interpretation

The LCA presented in this chapter highlights the importance of modelling choices and differences between the two mining alternatives. Several outcomes of the LCA align with the findings from the previous LCA studies presented in Chapter 5, but there are also interesting deviations and new insights. As in earlier studies, the baseline results show that deep-sea mining generally has lower impact values compared to land-based mining, making it the more favourable alternative. However, the choice of electricity source in both systems significantly affects the outcomes. In certain scenarios, this results in the impacts of deep-sea mining exceeding those of land-based mining, making land-based mining the more advantageous option.

Furthermore, the sensitivity analyses reveal that the results are sensitive to the choice of allocation method. In contrast, variations in the market values, impact assessment methods, horizontal transport distances, or electricity consumption in the deep-sea mining model lead to minor changes in the results. This indicates that the results of this LCA are not sensitive to these factors.

This subsection elaborates on the results of each impact category and the influence of specific modelling choices. The scenario, contribution, and sensitivity analyses are used to explain the outcomes.

### 6.11.1. Climate Change & Energy Resources

The lower potential impacts of deep-sea mining on climate change and energy resources in the baseline model can be explained mainly by how electricity consumption is modelled in both systems. The contribution analysis reveals that processing the nodules contributes most to the climate change impacts of the deep-sea mining system, mainly due to energy use. For the land-based mining alternative, energy is also the main contributor, driven by nickel production. Notably, the land-based mining system requires almost four times more electricity than the deep-sea mining system. This difference is mainly because polymetallic nodules have higher ore grades, which substantially reduces the energy needed for processing.

Furthermore, the impacts on climate change and energy resources of the deep-sea mining model decrease when the electricity for processing the nodules is replaced with renewable energy sources. Conversely, applying carbon-intensive electricity mixes, such as the Indian or Indonesian mix (Ember, 2024, 2025b), lead to higher impacts. Nevertheless, even under these less favourable electricity scenarios, the difference compared to the initial land-based alternative remains large. As a result, the deep-sea mining alternative continues to appear more beneficial across different electricity sources for nodule processing, when the land-based system remains unchanged.

However, the impacts also depend on the choice of electricity source in the land-based mining model. In the baseline model, the metal production is based on the top-producing countries of nickel, copper, and cobalt. Nickel production is the major contributor to the impacts on climate change and energy resources. Global nickel production is dominated by Indonesia (USGS, 2025), and the electricity mix of this country heavily relies on fossil fuels (Ember, 2024). Consequently, the climate change and energy resources impacts for the baseline land-based mining system are relatively high. These impacts increase even further in a scenario where all electricity for metal production comes from Indonesia. Similar patterns are observed when considering other major producing countries such as China and the Philippines, which also have carbon-intensive electricity mixes (Ember, 2025a, 2025d; USGS, 2025). In contrast, when the electricity is sourced from countries with renewable-rich mixes, such as Denmark, the DRC, Norway, or Paraguay (Bindman, 2023; Ember, 2025c; WindEurope, 2024), the climate change and energy resources impacts of the land-based mining system become much lower.

The same holds for the global average electricity process from Ecoinvent. As explained by Ecoinvent (2025b), this process includes a large share of Alpine hydropower, because country-specific data on electricity emissions were limited when this dataset was developed. As a result, using this electricity source makes the land-based system appear to have lower climate change and energy resource impacts than deep-sea mining. This aligns with the findings of Fritz et al. (2023), who observed that when they used the Ecoinvent dataset instead of a land-based model based on real mining projects, the climate change impacts of deep-sea mining became about 28% higher than the land-based mining alternative.

Overall, the choice of electricity source plays a critical role in the climate change and energy resources impact categories. When renewable-rich electricity mixes are applied, these potential impacts are

significantly reduced. This effect is particularly significant in the land-based mining model, as it consumes substantially more electricity than the deep-sea mining system and the percentage contribution of energy processes is higher for land-based mining. As a result, under renewable electricity scenarios, land-based mining becomes more favourable than deep-sea mining of polymetallic nodules. Therefore, this modelling choice is important for the climate change and energy resources outcomes of the LCA.

### 6.11.2. Water use

The results of the baseline model show that the potential water use is higher when the metals come from land-based mining than from deep-sea mining. This is also mainly due to energy consumption, as the energy processes in the land-based mining system are responsible for almost all the water use.

When the electricity source for metal production in the land-based system is changed to a hydropower-based mix, water use of the land-based system increases significantly. This is the case for Norway and Ecoinvent's global average for electricity production. This increase occurs because these mixes rely heavily on reservoir-based hydropower, which has the highest water footprint of all electricity sources (Buli, 2025; European Commission, 2019). In contrast, the electricity mixes of the DRC and Paraguay, which also rely on hydropower, do not lead to the same increase in water use because their hydropower comes from large dams rather than reservoirs. When electricity sources with a lower share of reservoir-based hydropower are used in the land-based mining system, its water use decreases. As a result, applying the electricity mixes of Chile, the DRC, or Paraguay in the land-based system leads to the deep-sea alternative having higher water use impacts compared to land-based mining.

A similar pattern occurs for the electricity source used for processing the nodules in the deep-sea mining model. When this electricity source is changed from the Japanese mix to hydropower, the water use of the deep-sea alternative increases significantly, even exceeding the impacts of the land-based mining system. This highlights the trade-offs involved in locating the nodule processing plant near hydropower resources and demonstrates how the choice of electricity source significantly affects water use impacts.

### 6.11.3. Ionising Radiation

Similar to the impact categories that will be discussed in Subsection 6.11.5, waste treatment is a major contributor to ionising radiation impacts for both mining alternatives. Additionally, this impact category is also sensitive to the choice of electricity source in both systems. In the baseline scenario, the deep-sea alternative shows lower potential ionising radiation impacts than the land-based alternative. However, when the electricity source for processing nodules is changed from the Japanese mix to nuclear power, the ionising radiation impacts of the deep-sea system increase substantially, making the land-based alternative considerably more beneficial.

The same pattern occurs for the electricity source used in the land-based mining system. The ionising radiation impacts are significantly large when the electricity mix of the Russian Federation is used. This country has a relatively high share of nuclear power in the mix (Ember, 2025e). Conversely, using electricity mixes from countries with little or no nuclear power leads to lower ionising radiation impacts, making the land-based mining alternative more advantageous compared to deep-sea mining.

### 6.11.4. Ozone depletion, Acidification, Particulate Matter Formation & POF

Ozone depletion impacts are significantly higher when the metals come from land-based mining compared to deep-sea mining. In the deep-sea alternative, the potential ozone depletion impacts mainly come from the horizontal transport and processing of nodules. In the land-based system, these impacts are mainly due to nickel production. Additionally, energy processes are again major contributors to the impacts in both systems.

Ozone-depleting substances (ODS) are compounds that release bromine or chlorine when exposed to UV-light in the stratosphere, which contribute to ozone depletion (US EPA, 2025a). Electricity and heat from fossil fuels lead to more of these emissions and therefore more harm to the ozone layer (DFW Solar Electric, 2021). This explains why the scenario analyses show that applying renewable electricity sources leads to lower ozone depletion impacts. Nonetheless, even under these scenarios, the deep-sea mining alternative remains more beneficial.

A similar pattern is observed for terrestrial acidification, particulate matter formation, and photochemical oxidant formation (POF). The deep-sea alternative has significantly lower impacts on these categories,

and energy and transportation processes contribute most to the impacts of both systems. The combustion of fossil fuels for transportation or industrial use is a key contributor to terrestrial acidification, particulate matter formation, and photochemical oxidant formation (Patel, 2021; RIVM, 2025; Sarac, n.d.).

#### **6.11.5. Ecotoxicity, Eutrophication & Human toxicity**

Waste treatment is responsible for almost all the impacts on freshwater and marine ecotoxicity, fresh water and marine eutrophication, human toxicity, and ionising radiation in both mining alternatives. However, the land-based mining system results in significantly higher impact values compared to deep-sea mining.

For freshwater ecotoxicity, marine ecotoxicity, and non-carcinogenic human toxicity, this difference is mainly due to the sulphidic tailings generated from copper production in the land-based mining model. The contribution analysis indicates that copper production has the highest contribution to these impacts. Sulphidic copper tailings contribute to toxicity impacts by polluting natural environments, with heavy metals in particular leading to long-term consequences for ecosystems and human health (Adrianto et al., 2022).

For freshwater eutrophication, marine eutrophication, carcinogenic human toxicity, and ionising radiation, nickel production is the main contributor. While copper production creates the largest amount of sulphidic tailings, nickel production also generates sulphidic tailings as well as other outflows, including blast furnace sludge, nickel smelter slag, and spent solvent mixtures. For example, blast furnace sludge contributes to carcinogenic human toxicity, because it is a hazardous material that can cause lung cancer (USS, 2020).

In addition, polymetallic nodules have higher ore grades compared to land-based ores (Hein et al., 2013). A higher ore grade means that the amount of metal in the ore is higher, resulting in less waste generated per unit of metal. Consequently, this reduces the need for waste treatment and further explains why the deep-sea mining alternative shows substantially lower impacts in these categories.

In contrast to the other toxicity categories, terrestrial ecotoxicity is less dominated by waste treatment. In the deep-sea mining model, hydrometallurgical processing contributes most to terrestrial ecotoxicity, similar to the toxicity impact categories discussed above. However, horizontal transport plays a relatively larger role in terrestrial ecotoxicity compared to the other toxicity categories, highlighting that emissions during transport more strongly affect land-based ecosystems. Finally, it is notable that the absolute terrestrial ecotoxicity impacts, measured in kg 1,4-DCB-Eq, are significantly higher than those of the other toxicity impact categories, for both mining alternatives.

#### **6.11.6. Land Use & Transformation of Natural Land**

Lastly, the results show that the deep-sea mining alternative potentially leads to lower overall land use, but causes a larger transformation of natural land compared to land-based mining. The land use impact category, as defined in the ReCiPe 2016 method, measures the occupation of land ( $m^2 \cdot year$ ). Since deep-sea mining occupies the mining area for only a short period, its total land occupation over time is relatively low. However, deep-sea mining takes place across a much larger area, resulting in a greater direct transformation of land ( $m^2$ ). The extent of seabed transformation in the deep-sea mining alternative is so substantial that it exceeds the total transformation of natural land in the land-based mining alternative.

# 7

## Discussion

This study provided deeper insight into the life-cycle environmental impacts of deep-sea mining compared to land-based mining, emphasizing the influence of specific choices in LCAs on the results. This chapter elaborates on biodiversity & ecosystems impacts, as well as social, economic, and political considerations. In addition, other alternatives are discussed alongside deep-sea mining and land-based mining. Finally, this chapter addresses the study's key limitations.

### 7.1. Biodiversity & Ecosystems

LCA studies are limited to assessing generic environmental impacts and typically exclude impacts on biodiversity and ecosystems. This is a major limitation, as the debate on the environmental impacts of deep-sea mining is strongly focused on the potential effects on biodiversity and ecosystems. These impacts are location-specific, whereas LCA focuses on generic impacts that do not incorporate spatial ecological variability (Bromwich et al., 2025; Guinée et al., 2002).

Nevertheless, Pr eat et al. (2021) developed a framework to include biodiversity in LCAs on deep-sea mining. This was the first attempt to integrate biodiversity impacts on deep-sea ecosystems into LCA methodology. The framework used land transformation and occupation impacts, based on the understanding that land use change is a primary driver of biodiversity loss (De Baan et al., 2013; Pr eat et al., 2021). Similarly, De Baan et al. (2013) presented an approach for calculating the biodiversity loss from land use change in terrestrial ecosystems within LCA. However, although land use is the main driver of biodiversity loss, Knudsen et al. (2017) highlighted that other factors, such as pollution, can also contribute to biodiversity decline.

In addition, these approaches for incorporating biodiversity loss in LCA require detailed location-specific data on land types and ecosystems affected by mining activities. Impacts on biodiversity can vary significantly between regions and ecosystems, and site-specific data are often lacking (De Baan et al., 2013; Knudsen et al., 2017). Moreover, LCA is not well suited to assess such impacts, as it lacks spatial differentiation and does not account for location-specific ecological contexts (Bromwich et al., 2025).

Therefore, Bromwich et al. (2025) recommended using other location-specific methods alongside LCA to assess biodiversity and ecosystem impacts. For example, Ecological Risk Assessment (ERA) evaluates the likelihood that local ecosystems and species will be affected by mining activities. ERA involves identifying potential environmental stressors, assessing exposure and effects on ecosystems and their components, and characterizing the overall risk (US EPA, 2025b). Unlike LCA, ERA takes into account site-specific conditions, making it a valuable complement for assessing biodiversity and ecosystem impacts (US EPA, 2025b).

In addition, biodiversity can be measured in multiple ways. It is commonly expressed as species density, which is the number of different species in a given area or volume (Guinée et al., 2002). However, the literature distinguishes two other approaches. The first considers the type of species, which refers to the unique value of the genetic code of the species (Guinée et al., 2002). The second focuses on ecosystem diversity, which accounts for the number of different habitats and the relationships between species

and their environments (Guinée et al., 2002; IFAD, 2024). In addition, biodiversity can be measured on different scales, such as regional or global biodiversity (Weiskopf et al., 2024).

Furthermore, as a follow-up on the study of Paulikas et al. (2020b) (see Chapter 5), TMC commissioned a study by Katona et al. (2023) on the challenges of comparing biodiversity impacts of land-based and deep-sea mining (The Metals Company, 2024b). The authors emphasized that biodiversity is a complex concept that is difficult to quantify and compare across different systems. They argued that quantitative measurements alone are insufficient and should be supplemented with qualitative assessments.

In addition to the challenges in quantifying biodiversity and ecosystem impacts, much remains unknown about the long-term impacts of deep-seabed mining. As discussed in Section 2.1, previous research has shown that noise, vibrations, lights, scraping on the seabed, removal of nodules, discharges to water, and formation of sediment plumes harm marine life (IUCN, 2024; JPI Oceans, 2022; Koschinsky et al., 2018; Weaver et al., 2022). However, the long-term consequences for marine species and ecosystems remain uncertain (Goyette, 2025). Furthermore, the total area affected may far exceed the direct mining area, and it is still unclear how changes in marine environments may influence other interconnected parts of the Earth system (Goyette, 2025). Since the ocean is the largest carbon storage on Earth, disruption of its ecosystems could also exacerbate the climate crisis (IUCN, 2024).

Moreover, there are large scientific gaps about species and ecosystems in both marine and terrestrial environments. It is estimated that 91% of marine species and 86% of terrestrial species remain undiscovered (Metaxas et al., 2024; Mora et al., 2011). These gaps pose significant challenges to environmental assessments (Amon et al., 2022). Addressing them requires substantial scientific effort and time (Amon et al., 2022). Without this knowledge, it is not possible to fully understand the potential impacts of deep-sea mining on biodiversity and ecosystems (Amon et al., 2022). In addition, knowledge about marine ecosystems is much more limited than knowledge about terrestrial ecosystems (Danovaro, 2024). This further complicates the comparison between land-based and deep-sea mining.

To conclude, LCA lacks the ability to quantify biodiversity and ecosystem impacts. These impacts come with many uncertainties, can be measured in different ways, and are affected by a lack of site-specific data and broader scientific gaps on species and ecosystems. Nevertheless, these impacts cannot be excluded from the environmental impact assessment, as existing research has shown that deep-sea mining could lead to significant and potentially irreversible impacts on biodiversity and ecosystems. Therefore, LCAs should be complemented with additional methods capable of quantifying such effects to provide a more comprehensive and realistic evaluation.

## 7.2. Social & Economic Considerations

Land-based mining is a major global economic driver and a key source of employment, with approximately 30 million people working in the sector (Baraza et al., 2023). Each year, the mining industry contributes around \$1.9 trillion to the global economy (Escamilla, 2024). However, this sector also has the highest accident rate, resulting in approximately 15,000 fatalities annually (Baraza et al., 2023). In addition, land-based mining is considered a threat to the health of local residents and their quality of life (Mononen et al., 2022). Additionally, land-based mining increasingly leads to displacement of communities, loss of livelihood, and land use conflicts (Gukurume & Tombindo, 2023; Hilson, 2002).

In comparison, deep-sea mining is also expected to generate significant economic revenue. The total value of polymetallic nodules in the CCZ is estimated to be around \$18.4 trillion (Epikhin et al., 2024). However, this primarily benefits mining companies, investors, and developed countries. The UNCLOS defines the international seabed as "common heritage of humankind", meaning that its resources should benefit all people (Baker, 2024). This principle specifically aims to support the interests of developing countries (Bourrel et al., 2018). Nevertheless, without compensation, developing countries are expected to face negative effects on their economies (Planet Tracker, 2024). While all technologies used in deep-sea mining are controlled by wealthier nations, most sponsoring states are developing countries (ISA, 2021). The ISA aims for benefit-sharing arrangements that allocate the revenues of deep-sea mining in ways that lead to reducing poverty, but these arrangements have not yet been finalized (ISA, 2021).

Deep-sea mining can also negatively affect local communities that depend on the ocean (IUCN, 2024). The cultures and identities of Small Island Developing States (SIDS) are fundamentally connected to the sea (ISA, 2021). Their economies are sustained by the oceans, especially through fishery (ISA, 2021).

These fisheries provide food, employment, and revenue for local communities, such as the Pacific island communities (Jaeckel et al., 2023). They can experience negative impacts from the noise, contamination, and sediment plumes generated by mining operations (Jaeckel et al., 2023).

Paulikas et al. (2020b) were the first to include social and economic impacts alongside environmental impacts in a life-cycle assessment comparing deep-sea and land-based mining. They found that deep-sea mining could lead to a substantial reduction in employment opportunities compared to land-based mining, but also concluded that it could result in fewer human lives being put at risk.

Furthermore, the development of deep-sea mining and associated investments rely heavily on regulations. The absence of finalised exploitation regulations (see Section 7.3) prevents deep-sea mining companies from beginning commercial operations. For example, Loke Marine Minerals recently went bankrupt due to the lack of exploitation rules, which weakened investor interest (Khan, 2025). In addition, TMC stated that they are ready to start mining and only require a robust regulatory regime (The Metals Company, 2025a). However, commercial extraction also requires scaling up Allseas' nodule collector, which was used in TMC's pilot tests (Ackerman, 2025). Given that this is very capital-intensive, the company is waiting for regulatory approval before committing to such a major investment (Ackerman, 2025).

Another discussion point is monitoring and ensuring that mining organisations comply with the ISA rules and environmental safeguarding. According to Articles 139 and 153 of UNCLOS (1982), States Parties are responsible for ensuring effective control over mining activities in international waters. However, monitoring and enforcing environmental safeguarding in remote, out-of-sight locations at great ocean depths is challenging (Jackson & Chakraborty, 2025). It requires advanced technologies and logistical resources that entail significant financial demands, often exceeding the capacities of the responsible nations and even the ISA itself (Sustainability Directory, 2025).

In conclusion, the discussion of deep-sea mining in comparison with land-based mining should also address social and economic considerations alongside environmental impacts. This includes issues of safety, livelihoods, cultural heritage, and the fair distribution of benefits and burdens. Additionally, the costly monitoring of deep-sea mining needed for environmental protection raises questions about who will finance it. This section highlights the urgent need for strong international regulations, as well as benefit-sharing agreements to ensure equity.

### 7.3. Geopolitical Considerations

Increasing geopolitical tensions are causing supply risks of CRMs from land-based mining (IEA, 2025b). CRMs are currently sourced from a limited number of resource-rich countries (IEA, 2025b). Since 2023, export restrictions are increasing because of growing strategic competition (IEA, 2025b). Concerns are rising about the security of supply, highlighting the urgency to strengthen the diversity and resilience of supply (European Commission, 2025; IEA, 2025b; TNO, 2023). Deep-sea mining can potentially diversify global CRM supply and reduce reliance on geopolitically uncertain sources (Vivoda, 2024).

Unlike land-based mining, which falls under national jurisdiction, deep-sea mining typically concerns areas beyond national borders. The international law of the sea recognizes the following maritime zones, listed in increasing order of distance from the coast: 1) Internal waters, 2) Territorial sea, 3) Contiguous zone, 4) Exclusive Economic Zone (EEZ), 5) Extended Continental Shelf (ECS), 6) International seabed (NOAA, 2024). A schematic overview of these maritime zones is presented in 7.1.

The last two areas are referred to as international waters, which fall outside national jurisdiction. The ISA is currently responsible for regulating deep-sea mining in international waters (ISA, 2025a). Since 2014, the ISA has been trying to develop the Mining Code, which is a regulatory framework of rules, regulations, and procedures (RRP) for the prospecting, exploration, and exploitation of sea minerals in international waters (ISA, 2025c). However, to date, the ISA has failed to finalize the RRP for exploitation, and therefore the ISA is under increasing pressure (Pickens et al., 2024).

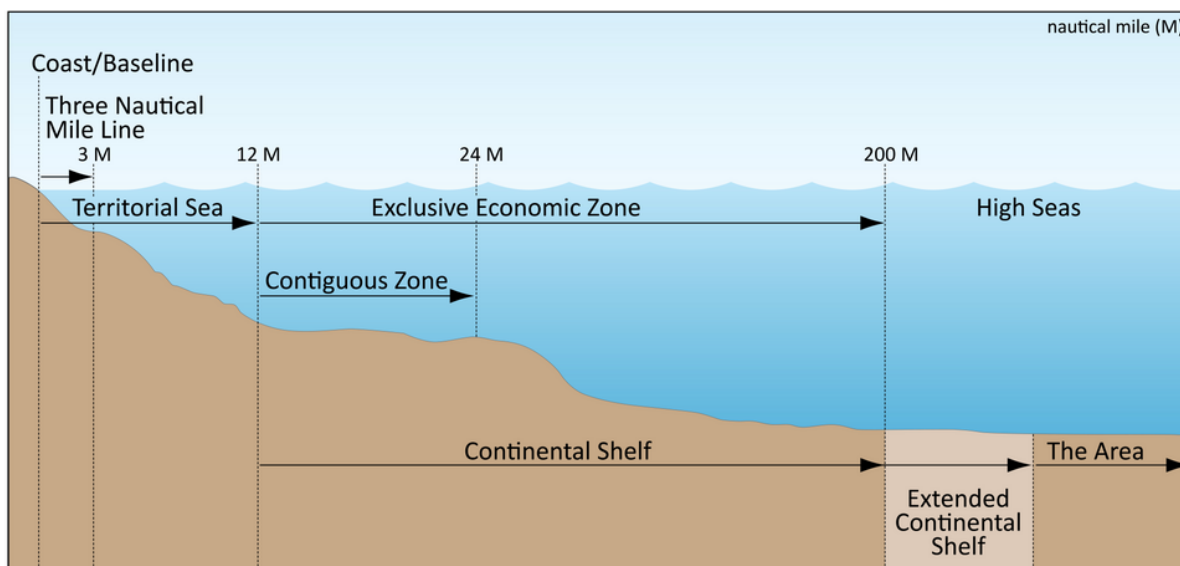


Figure 7.1: Maritime zones according to the international law, from NOAA (2024).

Currently, 169 states and the EU joined the ISA, but the USA is not one of them (Baskaran & Schwartz, 2025; ISA, 2025b). President Trump recently revealed an executive order to secure the offshore critical minerals (Baskaran & Schwartz, 2025). The Trump administration signed this order to counter the mineral dominance of China (Trump, 2025). The ISA responded with a formal statement of disapproval and criticism (ISA, 2025d). The statement emphasized that no state holds the right to explore or exploit minerals in international waters outside the legal framework of the UNCLOS, and that this also applies to states that have not ratified the UNCLOS.

In contrast, nations have the right to explore and exploit mineral resources within their maritime zones under national jurisdiction, such as the EEZ. The Cook Islands are leading in EEZ deep-sea mining, having issued exploration contracts and targeting commercial production by 2028 (Gales, 2024). Other countries actively exploring minerals within their EEZ are Norway, China, Japan, Sweden, Namibia, India, Saudi Arabia, American Samoa, Papua New Guinea, South Africa, Brazil, and Chile (Gales, 2024). Papua New Guinea was one of the first countries to allow deep-sea mining in its EEZ through the Solwara 1 project, operated by Nautilus Minerals. However, this project ended unsuccessfully after Nautilus declared bankruptcy in 2019 (Gales, 2024). Beyond deep-sea mining, shallow-water mining has been commercially active for decades (Kaikkonen & Virtanen, 2022). For example, Royal IHC develops technologies for extracting gravel, sand, diamonds, and other commodities from shallow waters (Royal IHC, 2025). While shallow-water mining has long been commercially viable, deep-sea mining is not yet commercially operational, and the main interest of deep-sea mining remains on international waters. (Ashford et al., 2025).

To conclude, the discourse surrounding deep-sea mining is highly intertwined with geopolitical tensions of both land-based and deep-sea mining. As countries compete to secure their supply of CRMs, deep-sea resources offer opportunities to extend and diversify supply. Nonetheless, deep-sea mining also introduces political tensions, especially in international waters beyond national jurisdiction. The future of deep-sea mining strongly depends on how geopolitical tensions evolve.

## 7.4. Other Alternatives

This study focused on two alternatives to gain the metals needed for the energy transition: deep-sea mining and land-based mining. However, there are more alternatives. One option is to improve reusing and recycling practices and move towards a more circular economy. In a circular economy, materials remain in use for longer, and when products reach their end-of-life, their components are recovered and reintegrated into the production of new products (SINTEF, 2022). Before products reach their end-of-life, they should be reused. For instance, discarded EV batteries typically still contain about 80% of their capacity, making them suitable for other stationary applications in households, buildings, or industries (SINTEF, 2022). In contrast to reusing, recycling does not reduce overall mineral demand,

but it substitutes mineral extraction (SINTEF, 2022). Currently, technologies continue to advance and recycling rates are increasing (Guo et al., 2023). However, according to Guo et al. (2023) recycling is not enough to satisfy the rapidly growing metal demand. The authors pointed out that losses are unavoidable and infinite recycling is not possible.

Another alternative is urban mining, a practice in which valuable metals are recovered from urban infrastructures and products (Van der Voet et al., 2025). This practice aligns with circular economy principles and is considered a sustainable alternative to conventional mining (Abdelhamid et al., 2025). Urban mines could become significant sources of critical materials, but achieving this requires major organizational changes and will take a long time to realise (Van der Voet et al., 2025). Further, similar to recycling, urban mining currently cannot meet the high demand for metals. However, Van der Voet et al. (2025) emphasized that the worst thing we could do is dismissing circularity as unimportant because secondary materials on their own currently cannot meet the demand.

Furthermore, technological innovations can play an important role. Innovations in material efficiency result in lower material demand (Carrara et al., 2023). In addition, improving technologies for extracting minerals from mine tailings leads to more available materials (Metaxas et al., 2024). Innovations are also focusing on substituting critical raw materials by non-critical materials (Metaxas et al., 2024). For example, sodium-ion batteries have been developed as an alternative to lithium batteries (Wang et al., 2024). These Na-ion batteries offer a cheap alternative made of a widely available material (TU Delft, 2024). According to SINTEF (2022), shifting away from lithium batteries in stationary applications and diversifying EV battery chemistries could reduce demand for nickel, cobalt, and manganese by 40–50% between 2022 and 2050. However, substituting CRMs is challenging, as many materials have limited alternatives that do not significantly influence performance and costs (IEA, 2025b).

Finally, the demand for critical raw materials can be reduced by behavioural change. For example, changes in use-patterns, appliances, and mobility can result in less energy demand, and therefore less demand for critical materials (Carrara et al., 2023). However, there are barriers that allow for behavioural change to happen. Changing habits and routines is hard due to preference for current practices, inertia, comfort, social norms, and lack of awareness (IEA, 2021a). In addition, barriers for behavioural change go beyond individual choices and also include systemic aspects, such as the availability of sustainable transport alternatives (IEA, 2025a).

In conclusion, deep-sea mining is not the only alternative for conventional land-based mining. Opportunities exist in reusing, recycling, urban mining, technological innovations, and behavioural change. However, each of these alternatives comes with challenges and are currently insufficient to meet the large metal demand on its own. Therefore, the discussion remains whether to prioritise deep-sea mining, alternative solutions, or a combination to meet the critical material needs of the energy transition.

## **7.5. Research Limitations**

This study acknowledges limitations that should be taken into account when using its results. These limitations are mainly due to data availability.

### **7.5.1. Comparative Analysis**

The comparative analysis (Chapter 5) was primarily based on published documents of the five previous LCA studies. The authors of all studies were contacted to request additional information and data, but only Fritz et al. (2023) and Paulikas et al. (2020b) provided this. Fritz et al. (2023) shared their final report on which they based their publication. This report included additional data and more detailed information that proved valuable for the comparative analysis. Additionally, Paulikas et al. (2020b) provided the technical appendix of their study. This document clarified that the same data and assumptions were used in the two studies by Paulikas et al. (2020b, 2020a), indicating that they used the same LCA model, focusing on different impact categories.

Furthermore, for some of the five previous LCA studies, flowcharts and unit-process tables were available, but their LCA models were not shared. The comparison could have been more comprehensive if the authors had provided the original models used in LCA software such as OpenLCA. Access to these models would have offered deeper insight into the influence of specific modelling choices and variations in them.

### 7.5.2. Deep-Sea Mining Model

The deep-sea mining model of the aligned LCA (Chapter 6) also has limitations that prevent a fully accurate representation of reality. It is a project-based model focused on the NORI project of TMC. The data is mainly based on previous LCA studies, rather than primary data from deep-sea mining organisations. The data sourced from the LCA study of Benchmark Mineral Intelligence (2022) is also based on the NORI project of TMC. However, this study was conducted prior to the pilot test of this project and therefore does not incorporate the results of this test. In addition, the processes in the model were highly aggregated due to the lack of more granular data.

Another important discussion point concerns the selection of metals included in the "basket" of final products. In the aligned LCA study, nickel, copper, and cobalt were considered final products. However, polymetallic nodules also contain large quantities of manganese. In PAMCO's pyrometallurgical processing plant, two product streams are produced: Ni-Cu-Co matte and MnSi slag. The matte undergoes hydrometallurgical processing to refine it into nickel cathode, cobalt-powder, and copper cathode. In contrast, the MnSi slag was not further processed in the model due to the absence of available data. According to TMC (2023b), MnSi is directly used by the steel industry, meaning it can be seen as a final metal product. However, MnSi slag is not a product from land-based mining and is therefore not comparable. In addition, unlike nickel, cobalt, and copper, manganese is not classified as a "key energy mineral" (IEA, 2025b). Therefore, the comparison focused on the environmental impacts associated with the production of nickel, cobalt, and copper. Similarly, Paulikas et al. (2020b, 2020a) chose a functional unit of one billion EVs, which includes only 5% of the manganese in polymetallic nodules. Fritz et al. (2023) pointed out that this model choice does not allow concluding that metal production from nodules has less climate change impacts than from land-based ores. Consequently, the aligned LCA study in Chapter 6 is limited to nickel, copper, and cobalt.

In addition, a constant moisture content and ore grade are assumed. The assumed moisture content is in line with the NORI area (Planet Tracker, 2023). In addition, the grade of nodules in the CCZ is estimated to be consistent across the area (AMC, 2021). However, in reality, each nodule is different and can vary in moisture contents and ore grades. For example, a lower ore grade means more nodules are needed to obtain the same amount of metal, which also increases the energy required and the waste produced.

Furthermore, the deep-sea mining model assumed an airlift for vertical transport, as it used data from Benchmark Mineral Intelligence (2022) and was based on TMC's NORI project. However, the hydraulic lift is considered the core vertical transportation technology (De Hoog, 2024). While TMC uses an airlift in its system, organisations such as GSR and IOM apply hydraulic lifts (Zhang et al., 2025). In addition, the airlift is more energy-intensive than the hydraulic lift (Hu et al., 2022). Therefore, the LCA results can differ when other deep-sea mining systems are applied. However, the contribution analysis showed that the impacts are mainly due to the onshore processing of the nodules rather than the offshore processes, such as the vertical transport. It is thus expected that the impact results will change more when a different processing route is assumed than when a different extraction system is applied. For this study, the TMC system was assumed, because it is currently the most developed system to start commercial deep-sea mining. However, this could change in the future, and the model could also be based on a combination of different systems.

In addition, the PAMCO plant has proven to be a realistic processing plant for the pyrometallurgical processing step. However, there are currently no operating processing plants for the hydrometallurgical processing steps. It was assumed that this step takes place at the same location as PAMCO's plant and therefore also uses the Japanese electricity mix, but this is not an accurate representation of reality. Therefore, the model can be improved when such processing plants are set up and data become available.

Lastly, the deep-sea model represented commercial deep-sea mining of nodules, while in reality the extraction and processing of deep-sea nodules is not yet in commercial operation. The data were based on exploration research and scaled to commercial scale. However, this may lead to results that differ from reality.

### 7.5.3. Land-Based Mining Model

The land-based mining model was based on the Ecoinvent database and therefore has certain limitations. First, this database does not include a process specifically for cobalt-powder production. Cobalt-powder mainly consists of cobalt (99.8%), but also contains impurities (Metal 3DP, 2024). Since the production

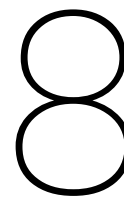
of pure cobalt is available in Ecoinvent, it was used as proxy. Although cobalt makes up nearly 100% of cobalt-powder, pure cobalt is not exactly equivalent to the cobalt-powder from the deep-sea mining model.

Furthermore, the Ecoinvent processes for metal production involve both mining and refining activities. The included locations of these processes in the land-based mining model were based on data from USGS (2025) on the top-producing countries. These are the countries that mine the most of these metals. USGS (2025) distinguished between mining and refining countries, but they did not provide values for the refining countries for each metal. Therefore, the locations for producing the metals from land-based mining reflected mining countries, even though the Ecoinvent processes also involves refining. Unlike nickel and copper, cobalt is mainly refined outside of the mining countries. China dominates global cobalt refining and was therefore included as a production location. However, this remains an imperfect representation of reality. The same holds for the other metals. Although nickel and copper are refined in countries similar to where they are mined, the amounts of mining and refining differ, resulting in varying contribution shares. Ideally, the land-based mining system would include separate mining and refining processes, based on the largest mining and refining countries of the three metals. This limitation is due to the structure of Ecoinvent database and missing data from USGS (2025) on the top-refining countries.

In addition, the land-based mining model was based on global averages from multiple mining projects, whereas the deep-sea mining model was project-based. Another option would be to develop a project-based land-based mining model by focusing on specific mining operations. For example, Fritz et al. (2023) based their land-based model on the Kevitsa, Murrin Murrin, and Woodie Woodie projects. However, it should be noted that land-based mining is more mature and involves numerous active projects, while deep-sea mining is much newer with only a few potential projects.

Lastly, there is a difference in how the land-based and deep-sea mining models were constructed. The deep-sea model was developed directly by the researcher, whereas the land-based model was primarily developed by Ecoinvent. As a result, the two models were not built in the same way, which may introduce inconsistencies and limit the fairness of the comparison. Ideally, both models would be developed following a similar modelling strategy to ensure a more robust comparison.

To conclude, this study faces several limitations primarily related to data availability and model design. The comparative analysis relied heavily on published data with limited access to original LCA models, restricting deeper insight into modelling choices. The deep-sea mining model of the aligned LCA used aggregated data, focused on a limited set of metals, and assumed technologies and process routes that may evolve. The land-based mining model, drawn from the Ecoinvent database, combined mining and refining data without distinguishing locations accurately, and is based on global averages rather than specific projects. Differences in model development approaches further challenged direct comparison between deep-sea and land-based mining. Recognising these constraints is essential when interpreting the results and it highlights opportunities for future research.



# Conclusions & Recommendations

This chapter presents the study's final conclusions and recommendations, addressing the main research question: **"How can LCA be used to support (policy) decisions on mining metals from deep-sea polymetallic nodules compared to land-based mining, and what are its main limitations in this context?"**. It is important to recognise that LCA focuses on generic environmental impacts and does not capture impacts on biodiversity and ecosystems, which are of key concern in deep-sea mining. For this reason, the study placed greater emphasis on generic environmental impacts such as climate change, acknowledging that biodiversity-related impacts fall outside of what LCA can adequately evaluate.

## 8.1. Conclusions

The objective of this study was to assess the potential environmental impacts throughout the life cycle of metals extracted from deep-sea polymetallic nodules compared to those from land-based ores. Specifically, the study aimed to evaluate how LCA can inform (policy) decisions in this context. LCA is currently used to support claims that metals from deep-sea mining are environmentally preferable, even though LCA does not capture location-specific impacts, and previous LCAs in this context show considerable variation in outcomes. The research combined a comparative analysis of previous LCA studies, the development of an aligned LCA, and a critical discussion.

The first subresearch question, **"What are the outcomes of previous LCA studies on metals from deep-sea polymetallic nodules compared to land-based mining?"**, was addressed through a comparative analysis of the previous LCAs. These five studies focused mainly on the impacts on climate change. All studies concluded that metals from deep-sea mined polymetallic nodules potentially cause less climate change than metals from land-based mining, making deep-sea mining more beneficial. However, the magnitude of this advantage varied considerably. On top of this, the study showed that three LCAs that reported larger differences in favour of deep-sea mining were supported by the deep-sea mining company TMC with sponsoring state Nauru, which strongly advocates deep-sea mining. The other two studies concluded a smaller difference and were supported by GSR (Belgium) and BGR (Germany). Belgium and Germany take a middle-ground position that supports deep-sea mining under strict rules and environmental safeguarding. This pattern highlights the importance of considering potential sponsor influence when interpreting LCA outcomes and underscore the need for independent, transparent assessments.

The comparative analysis also addressed the second subresearch question: **"What are the most significant causes of differences in the outcomes of these LCAs?"**. The variation in outcomes was due to methodological choices, data, and assumptions, particularly concerning energy consumption. All studies agreed that offshore processes of deep-sea mining contribute relatively little to the climate change impacts, while the majority of emissions come from onshore processing of the nodules, particularly from the energy-intensive pyrometallurgical refining. The studies supported by TMC assumed lower energy requirements for processing the polymetallic nodules into the refined metals. In addition, these studies assumed 100% renewable electricity for processing the nodules, based on the argument that processing plants can be located flexibly to ensure access to renewable energy sources. Conversely, the

two studies supported by GSR and BGR assumed electricity sources that include fossil fuels, which reduced the perceived environmental benefits of deep-sea mining compared to land-based mining. This key difference in LCA model choices explained why the TMC-supported studies showed more beneficial results for deep-sea mining. This distinction was especially relevant given that all studies assumed that land-based mining relies on electricity mixes dominated by fossil fuels.

The third subresearch question, "**How can these previous LCAs be aligned?**", was addressed through the development of an LCA that integrated data from the previous LCAs with recent developments in the field. The results of this LCA also answered the fourth subresearch question: "**What can be concluded from this aligned LCA with regard to the life-cycle environmental impacts?**". In the baseline model, deep-sea mining outperformed land-based mining in all ReCiPe 2016 midpoint impact categories. However, land-based mining had substantially lower impacts on the transformation of natural land, including the seabed. Moreover, the lower impacts observed for deep-sea mining on the ReCiPe impacts depended on LCA model choices, especially concerning energy use. Carbon-intensive electricity sources significantly increased climate change and energy resources impacts, whereas renewable sources reduced them. This effect was particularly strong for land-based mining, which required more energy due to lower ore grades compared to polymetallic nodules and had a higher proportional contribution from energy processes. Under renewable electricity scenarios, land-based mining became more favourable than deep-sea mining for the climate change and energy resource impacts. Other categories were also influenced by the choice of electricity source. Hydropower caused high water use, while nuclear power resulted in significant ionising radiation. These findings highlighted the trade-offs between environmental impact categories and the importance of assumptions about energy use.

While LCA is a valuable method for evaluating environmental impacts across the life cycle, this study also discussed major limitations, thereby addressing the final subresearch question: "**What are the main limitations of LCA in this context, and how can they be addressed?**". LCAs are currently used, for instance by TMC, to support claims that deep-sea mining outperforms land-based mining environmentally. However, as this study showed, such conclusions depend heavily on model choices and are limited to generic environmental impacts, particularly climate change. The comparative analysis and aligned LCA of this study showed that climate change impacts are mainly driven by energy consumption. In deep-sea mining, this was primarily due to nodule processing, whereas the extraction phase contributed relatively little. Nevertheless, the extraction phase may cause other environmental impacts that are typically not quantified with LCA, including impacts on ecosystems and biodiversity. These impacts are difficult to quantify due to substantial uncertainties and scientific gaps regarding species and ecosystems. However, these impacts cannot be overlooked, as existing research has shown that deep-sea mining could lead to serious and potentially irreversible impacts on biodiversity and ecosystems. Therefore, LCA should be complemented with location-specific assessment methods to account for such impacts. Moreover, a comprehensive comparison between deep-sea and land-based mining should consider social, economic, and geopolitical dimensions alongside environmental considerations.

In conclusion, LCA can provide valuable insights for policy and decision makers when comparing metals sourced from deep-sea polymetallic nodules with land-based ores, especially for evaluating generic environmental impacts like climate change. However, its value relies on how transparently and consistently the LCA is carried out, with energy use being a major influence on the results. Since LCA does not account for location-specific impacts on biodiversity and ecosystems, or social and economic factors, it should be used alongside other assessment methods. This ensures that decisions about metal supply consider not only generic environmental impacts, but also the specific ecological and social conditions of the extraction site.

## 8.2. Recommendations

Policy and decision makers should use LCAs comparing deep-sea and land-based mining with caution and awareness of their limitations. Currently, policy makers are paying increasing attention to LCAs of metals. However, they should acknowledge the effect of model choices, data gaps, assumptions, and uncertainties. LCA results can be manipulated by varying the way the system is modelled. In addition, open access of peer-reviewed LCA studies should be promoted. At present, most LCAs on deep-sea mining are industry-supported and lack full transparency.

In addition, LCA results should not be interpreted in isolation. Biodiversity loss and ecosystem degradation, which are especially of concern in the context of deep-sea mining, must be integrated in decision making using complementary assessment methods. Broader social, economic, and geopolitical factors should also be considered. These include the equal distribution of benefits and burdens, protection of livelihoods and cultural heritage, governance related to CRM supply, and regulation of deep-sea mining in international waters.

Policy and decision makers should also remain focused on alternative strategies to support the energy transition. Opportunities lie in reusing, recycling, urban mining, technological innovations, and behavioural change. Such approaches can reduce material demand, lower energy consumption, and promote a circular economy that limits the need for primary resource extraction from land or the deep-sea. However, each of these alternatives comes with its own challenges. Further research is needed to assess whether deep-sea mining, alternative solutions, or a combination offers the most effective and responsible path for meeting the critical material needs of the energy transition.

Further research should also try to fill existing scientific gaps. To fully understand the potential impacts of deep-sea mining, more information is needed on the long-term effects on marine life, ecosystems, and interconnected Earth systems. This also includes assessing the ratio between the mined area and the total affected area, as optimising this ratio could help reduce the environmental impacts per unit of production or enable scaling up extraction without increasing the ecological footprint. In addition, to compare the environmental impacts of metals from deep-sea mining and land-based mining, knowledge gaps related to both marine and terrestrial species and ecosystems must be addressed.

Overall, this study provides valuable insights to inform the ongoing debate on deep-sea mining. Although it does not offer definitive conclusions on whether deep-sea mining is environmentally preferable to land-based mining, it identifies conditions under which deep-sea mining results in lower impacts on certain generic environmental categories. The study also highlights key data gaps, uncertainties, and discussion points, guiding policy makers and future research in the field.

# References

- Abdelhamid, M. B., Casadella, V., & Tahi, S. (2025). Optimizing urban mining investments: Leveraging sequential compound real option analysis for circular economy transition. *Environmental Modeling & Assessment*. <https://doi.org/10.1007/s10666-025-10034-0>
- Ackerman, D. (2025). *Trump wants to “unleash” deep-sea mining. how soon could it start?* [Seabed spotlight]. <https://seabedspotlight.substack.com/p/trump-wants-to-unleash-deep-sea-mining>
- Adrianto, L. R., Pfister, S., & Hellweg, S. (2022). Regionalized life cycle inventories of global sulfidic copper tailings [Publisher: American Chemical Society]. *Environmental Science & Technology*, 56(7), 4553–4564. <https://doi.org/10.1021/acs.est.1c01786>
- Alhaddad, S., Mehta, D., & Helmons, R. (2023). Mining of deep-seabed nodules using a coandă-effect-based collector. *Results in Engineering*, 17, 100852. <https://doi.org/10.1016/j.rineng.2022.100852>
- Allseas. (2025). *Polymetallic nodule collection*. <https://www.allseas.com/en/what-we-do/polymetallic-nodule-collection>
- Alvarenga, R., Pr at, N., Duhayon, C., & Dewulf, J. (2022). Prospective life cycle assessment of metal commodities obtained from deep-sea polymetallic nodules. *Journal of Cleaner Production*, 330, 129884. <https://doi.org/10.1016/j.jclepro.2021.129884>
- AMC. (2021). *Initial assessment of the NORI property, clarion-clipperton zone*. [https://www.sec.gov/Archives/edgar/data/1798562/000121390021029413/fs42021a1ex96-1\\_sustainable.htm](https://www.sec.gov/Archives/edgar/data/1798562/000121390021029413/fs42021a1ex96-1_sustainable.htm)
- Amon, D. J., Gollner, S., Morato, T., Smith, C. R., Chen, C., Christiansen, S., Currie, B., Drazen, J. C., Fukushima, T., Gianni, M., Gjerde, K. M., Gooday, A. J., Grillo, G. G., Haeckel, M., Joyini, T., Ju, S.-J., Levin, L. A., Metaxas, A., Mianowicz, K., . . . Pickens, C. (2022). Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Marine Policy*, 138, 105006. <https://doi.org/10.1016/j.marpol.2022.105006>
- Ashford, O., Baines, J., Barbanell, M., & Wang, K. (2025). What we know about deep-sea mining — and what we don't. <https://www.wri.org/insights/deep-sea-mining-explained>
- Baker, R. (2024). *Deep-sea mining versus the common heritage of humankind* [Investment magazine]. <https://www.investmentmagazine.com.au/2024/01/deep-sea-mining-versus-the-common-heritage-of-humankind/>
- Balasubramanian, A. (2017). *Rock blasting for mining*. [https://www.researchgate.net/publication/316158230\\_ROCK\\_BLASTING\\_FOR\\_MINING](https://www.researchgate.net/publication/316158230_ROCK_BLASTING_FOR_MINING)
- Baraza, X., Cuguer -Escofet, N., & Rodr guez-Elizalde, R. (2023). Statistical analysis of the severity of occupational accidents in the mining sector. *Journal of Safety Research*, 86, 364–375. <https://doi.org/10.1016/j.jsr.2023.07.015>
- Baskaran, G., & Schwartz, M. (2025). Trump's deep-sea mining executive order: The race for critical minerals enters uncharted waters. <https://www.csis.org/analysis/trumps-deep-sea-mining-executive-order-race-critical-minerals-enters-uncharted-waters>

- BBC. (2025). *Seven takeaways from ukraine minerals deal*. <https://www.bbc.com/news/articles/c5yg456mzn8o>
- Benchmark Mineral Intelligence. (2022). *The metals company – life cycle assessment for TMC’s NORI-d polymetallic nodule project and comparison to key land-based routes for producing nickel, cobalt and copper*. [https://metals.co/wp-content/uploads/2023/03/TMC\\_NORI-D\\_LCA\\_Final\\_Report\\_March2023.pdf](https://metals.co/wp-content/uploads/2023/03/TMC_NORI-D_LCA_Final_Report_March2023.pdf)
- Bindman, P. (2023). *Top ten cleanest power grids* [Energy monitor]. <https://www.energymonitor.ai/sectors/power/the-top-ten-cleanest-power-grids-countries/>
- BMWK. (2025). *Federal institute for geosciences and natural resources (BGR)*. <https://www.bmwk.de/Redaktion/EN/Artikel/Ministry/federal-institute-for-geosciences-and-natural-resources.html>
- Bolevich, M. (2021). *Life cycle assessment will play an important in decision making for deep-sea mining* [DSM observer]. <https://dsmobserver.com/2021/04/life-cycle-assessment-will-play-an-important-in-decision-making-for-deep-sea-mining/>
- Bourrel, M., Thiele, T., & Currie, D. (2018). The common of heritage of mankind as a means to assess and advance equity in deep sea mining. *Marine Policy*, 95, 311–316. <https://doi.org/10.1016/j.marpol.2016.07.017>
- Bromwich, T., White, T. B., Bouchez, A., Hawkins, I., zu Ermgassen, S., Bull, J., Bartlett, H., Bennun, L., Biggs, E., Booth, H., Clark, M., El Geneidy, S., Prescott, G. W., Sonter, L. J., Starkey, M., & Milner-Gulland, E. J. (2025). Navigating uncertainty in life cycle assessment-based approaches to biodiversity footprinting. *Methods in Ecology and Evolution*. <https://doi.org/10.1111/2041-210X.70001>
- Buli, N. (2025). Mild weather, dense snow in southern norway limit risk of spring flooding. *Reuters*. <https://www.reuters.com/business/environment/mild-weather-dense-snow-southern-norway-limit-risk-spring-flooding-2025-03-26/>
- Cagurangan, M.-V. (2024). *Nauru defends deep-sea mining plans: ‘the greatest risk is failing to seize the opportunity’* [Pactimes]. <https://www.pacificislandtimes.com/post/nauru-defends-deep-sea-mining-plans-the-greatest-risk-is-failing-to-seize-the-opportunity>
- Carrara, S., Bobba, S., Blagoeva, D., Alves, D. P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior, A. A., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., . . . Christou, M. (2023). *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – a foresight study* [JRC publications repository] [ISBN: 9789268003398 9789268004074 ISSN: 1831-9424, 1018-5593]. <https://doi.org/10.2760/386650>
- CEVA Logistics. (2025). *Watt hours per kilogram*. <https://www.cevalogistics.com/en/glossary/watt-hours-kilogram>
- Chandrasekhar, A., Quiroz, Y., & Viglione, G. (2024). *Q&a: What does deep-sea mining mean for climate change and biodiversity loss?* [Carbon brief]. <https://interactive.carbonbrief.org/deep-sea-mining/>
- Cheng, Y., Dai, Y., Zhang, Y., Yang, C., & Liu, C. (2023). Status and prospects of the development of deep-sea polymetallic nodule-collecting technology [Number: 5 Publisher: Multidisciplinary Digital Publishing Institute]. *Sustainability*, 15(5), 4572. <https://doi.org/10.3390/su15054572>
- Cherkashov, G. (2022). *Seafloor massive sulfides and potential future minerals*. [https://www.isa.org.jm/wp-content/uploads/2022/12/02\\_cherkashov.pdf](https://www.isa.org.jm/wp-content/uploads/2022/12/02_cherkashov.pdf)

- Dames & Moore & EIC Corporation. (1977). *Description of manganese nodule processing activities for environmental studies* [OCLC: 1451653178]. Dept. of Commerce, National Oceanic; Atmospheric Administration, Office of Marine Minerals ; for sale by the National Technical Information Services. <https://catalog.hathitrust.org/api/volumes/oclc/4193397.html>
- Danovaro, R. (2024). Understanding marine biodiversity patterns and drivers: The fall of icarus. *Marine Ecology, n/a*, e12814. <https://doi.org/10.1111/maec.12814>
- DB. (2023). *Energy efficiency | deutsche bahn annual report 2023*. <https://ibir.deutschebahn.com/2023/en/combined-management-report/green-transformation/climate-protection/energy-efficiency/>
- De Baan, L., Alkemade, R., & Koellner, T. (2013). Land use impacts on biodiversity in LCA: A global approach. *The International Journal of Life Cycle Assessment*, 18(6), 1216–1230. <https://doi.org/10.1007/s11367-012-0412-0>
- De Hoog, E. (2024). Transient hydraulic transport in pipelines. <https://doi.org/10.4233/uuid:63109a8b-fec3-48f3-85b4-10923801f093>
- De Vree, J. (n.d.). *Calorische waarde*. [https://www.joostdevree.nl/shtmls/calorische\\_waarde.shtml](https://www.joostdevree.nl/shtmls/calorische_waarde.shtml)
- Deep Sea Conservation Coalition. (2024). *Deep-sea mining moratorium* [Deep sea conservation coalition]. <https://deep-sea-conservation.org/solutions/no-deep-sea-mining/>
- Deep Sea Conservation Coalition. (2025). *Momentum for a moratorium*. <https://deep-sea-conservation.org/solutions/no-deep-sea-mining/momentum-for-a-moratorium/>
- Deep Sea Mining. (2024). *American samoa visualization*. [https://deepseamining.ac/3d\\_models/american\\_samoa#gsc.tab=0](https://deepseamining.ac/3d_models/american_samoa#gsc.tab=0)
- Dewulf, s. (2024). *A deep-sea dilemma: An analysis of EU member states' positions on deep-sea mining in international waters* [Universiteit gent]. [https://www.ugent.be/ps/politiekewetenschappen/gies/en/research/publications/honours\\_paper/academic-year-2023-2024/a-deep-sea-dilemma](https://www.ugent.be/ps/politiekewetenschappen/gies/en/research/publications/honours_paper/academic-year-2023-2024/a-deep-sea-dilemma)
- DFW Solar Electric. (2021). *Renewable energy and the preservation of the ozone layer* [DFW solar electric]. <https://www.dfwsolarelectric.com/blog/world-ozone-day>
- Drazen, J. C., Smith, C. R., Gjerde, K. M., Haddock, S. H. D., Carter, G. S., Choy, C. A., Clark, M. R., Dutrieux, P., Goetze, E., Hauton, C., Hatta, M., Koslow, J. A., Leitner, A. B., Pacini, A., Perelman, J. N., Peacock, T., Sutton, T. T., Watling, L., & Yamamoto, H. (2020). Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining [Publisher: Proceedings of the National Academy of Sciences]. *Proceedings of the National Academy of Sciences*, 117(30), 17455–17460. <https://doi.org/10.1073/pnas.2011914117>
- DSMA. (2019). *Global sea mineral resources NV*. <https://www.deepsea-mining-alliance.com/en-gb/global-sea-mineral>
- Ecoinvent. (2024). *Impact assessment*. <https://support.ecoinvent.org/impact-assessment>
- Ecoinvent. (2025a). *EcoQuery*. <https://ecoquery.ecoinvent.org/3.10.1/cutoff>
- Ecoinvent. (2025b). *Electricity production, cobalt industry - global - electricity, high voltage, cobalt industry | ecoQuery*. <https://ecoquery.ecoinvent.org/3.10.1/cutoff/dataset/22891/documentation?>

- Ecorys, MRAG, GRID Arendal, Seascope, GEOMAR, & TU Delft. (2014). Study to investigate the state of knowledge of deep-sea mining. [https://maritime-forum.ec.europa.eu/document/download/b7b7d928-cf3a-42ab-9bfd-9baa1a982a20\\_en?filename=FGP96656\\_final\\_rep.\\_formatted.\\_november\\_2014.pdf](https://maritime-forum.ec.europa.eu/document/download/b7b7d928-cf3a-42ab-9bfd-9baa1a982a20_en?filename=FGP96656_final_rep._formatted._november_2014.pdf)
- Ember. (2024). *Indonesia* [Ember]. <https://ember-energy.org/countries-and-regions/indonesia>
- Ember. (2025a). *Global electricity review 2025 - chapter 5: Major countries and regions* [Ember]. <https://ember-energy.org/latest-insights/global-electricity-review-2025>
- Ember. (2025b). *India* [Ember]. <https://ember-energy.org/countries-and-regions/india>
- Ember. (2025c). *Norway* [Ember]. <https://ember-energy.org/countries-and-regions/norway>
- Ember. (2025d). *The philippines* [Ember]. <https://ember-energy.org/countries-and-regions/philippines-the>
- Ember. (2025e). *Russia* [Ember]. <https://ember-energy.org/countries-and-regions/russia>
- Environment Foundation. (2018). *Mining methods • environment guide*. <https://www.environmentguide.org.nz/activities/minerals/mining-methods/>
- Epikhin, I., Stella, C., Chahine, A. H., Ghi, T., Pankov, A., Malkov, A., & Smaiti, M. (2024). SEABED MINING: A \$20 TRILLION OPPORTUNITY. [https://www.adlittle.com/sites/default/files/viewpoints/ADL\\_Seabed\\_mining\\_2024\\_0.pdf](https://www.adlittle.com/sites/default/files/viewpoints/ADL_Seabed_mining_2024_0.pdf)
- Escamilla, C. (2024). *The importance of mining in modern society | school of mining & mineral resources*. <https://mining.arizona.edu/news/importance-mining-modern-society>
- EUCAR. (2020). *Attributional vs. consequential LCA*. <https://www.eucar.be/wp-content/uploads/2020/08/20200820-EUCAR-Attributional-vs-Consequential-updated-2.pdf>
- European Commission. (2019). *Water footprint of EU energy consumption - european commission*. [https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/water-footprint-eu-energy-consumption-2019-10-29\\_en](https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/water-footprint-eu-energy-consumption-2019-10-29_en)
- European Commission. (2025). *Critical raw materials - european commission*. [https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials\\_en](https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en)
- Fan, Z., Jia, Y., Chu, F., Zhu, X., Zhu, N., Li, B., & Quan, Y. (2022). Effects of migration and diffusion of suspended sediments on the seabed environment during exploitation of deep-sea polymetallic nodules [Number: 13 Publisher: Multidisciplinary Digital Publishing Institute]. *Water*, 14(13), 2073. <https://doi.org/10.3390/w14132073>
- Fritz, B., Heidak, P., Vasters, J., Kuhn, T., Franken, G., & Schmidt, M. (2023). Life cycle impact on climate change caused by metal production from deep sea manganese nodules versus land-based deposits. *Resources, Conservation and Recycling*, 193, 106976. <https://doi.org/10.1016/j.resconrec.2023.106976>
- Gales, P. (2023a). *CCZ logistics* [Deep sea mining]. <https://www.deepseamining.ac>
- Gales, P. (2023b). *Options for processing polymetallic nodules* [Deep sea mining]. <https://www.deepseamining.ac>
- Gales, P. (2024). *11 countries developing subsea minerals in their EEZs* [Deep sea mining]. <https://www.deepseamining.ac>

- Gazis, I.-Z., de Stigter, H., Mohrmann, J., Heger, K., Diaz, M., Gillard, B., Baeye, M., Veloso-Alarcón, M. E., Purkiani, K., Haeckel, M., Vink, A., Thomsen, L., & Greinert, J. (2025). Monitoring benthic plumes, sediment redeposition and seafloor imprints caused by deep-sea polymetallic nodule mining [Publisher: Nature Publishing Group]. *Nature Communications*, 16(1), 1229. <https://doi.org/10.1038/s41467-025-56311-0>
- Gollner, S., Kaiser, S., Menzel, L., Jones, D. O., Brown, A., Mestre, N. C., Van Oevelen, D., Menot, L., Colaço, A., Canals, M., Cuvelier, D., Durden, J. M., Gebruk, A., Egho, G. A., Haeckel, M., Marcon, Y., Mevenkamp, L., Morato, T., Pham, C. K., . . . Martinez Arbizu, P. (2017). Resilience of benthic deep-sea fauna to mining activities. *Marine Environmental Research*, 129, 76–101. <https://doi.org/10.1016/j.marenvres.2017.04.010>
- Goyette, W. (2025). *Deep-sea mining's devastating impact on ocean life: The hidden cost of mineral extraction* [Marine biodiversity science center]. <https://www.marinebiodiversity.ca/deep-sea-minings-devastating-impact-on-ocean-life-the-hidden-cost-of-mineral-extraction/>
- GreenDelta. (2025). *openLCA* (Version 2.4.1). <https://www.openlca.org/>
- Greenpeace. (2025). *Stop deep sea mining* [Greenpeace international]. <https://www.greenpeace.org/international/act/stop-deep-sea-mining/>
- GSR. (2023). *The GSR patania II expedition*. [https://deme-gsr.com/wp-content/uploads/2023/03/GSR\\_FINAL\\_Smaller1-1.pdf](https://deme-gsr.com/wp-content/uploads/2023/03/GSR_FINAL_Smaller1-1.pdf)
- Guinée, J. B., De Bruijn, H., Van Duin, R., Huijbregts, M. A. J., Gorree, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S., & Udo De Haes, H. A. (Eds.). (2002). *Handbook on life cycle assessment: Operational guide to the ISO standards* (Vol. 7). Springer Netherlands. <https://doi.org/10.1007/0-306-48055-7>
- Gukurume, S., & Tombindo, F. (2023). Mining-induced displacement and livelihood resilience: The case of marange, zimbabwe. *The Extractive Industries and Society*, 13, 101210. <https://doi.org/10.1016/j.exis.2023.101210>
- Guo, J., Ali, S., & Xu, M. (2023). Recycling is not enough to make the world a greener place: Prospects for the circular economy. *Green Carbon*, 1(2), 150–153. <https://doi.org/10.1016/j.greenca.2023.10.006>
- Hein, J. R., Mizell, K., Koschinsky, A., & Conrad, T. A. (2013). Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews*, 51, 1–14. <https://doi.org/10.1016/j.oregeorev.2012.12.001>
- Heinrich, L., Koschinsky, A., Markus, T., & Singh, P. (2020). Quantifying the fuel consumption, greenhouse gas emissions and air pollution of a potential commercial manganese nodule mining operation. *Marine Policy*, 114, 103678. <https://doi.org/10.1016/j.marpol.2019.103678>
- Helmons, R., de Wit, L., de Stigter, H., & Spearman, J. (2022). Dispersion of benthic plumes in deep-sea mining: What lessons can be learned from dredging? [Publisher: Frontiers]. *Frontiers in Earth Science*, 10. <https://doi.org/10.3389/feart.2022.868701>
- Hilson, G. (2002). An overview of land use conflicts in mining communities. *Land Use Policy*, 19(1), 65–73. [https://doi.org/10.1016/S0264-8377\(01\)00043-6](https://doi.org/10.1016/S0264-8377(01)00043-6)
- Hu, Q., Li, Z., Zhai, X., & Zheng, H. (2022). *Development of hydraulic lifting system of deep-sea mineral resources*. <https://www.mdpi.com/2075-163X/12/10/1319>

- IEA. (2021a). *The potential of behavioural interventions for optimising energy use at home – analysis* [IEA]. <https://www.iea.org/articles/the-potential-of-behavioural-interventions-for-optimising-energy-use-at-home>
- IEA. (2021b). *The role of critical minerals in clean energy transitions*. <https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf>
- IEA. (2022). *Executive summary – norway 2022 – analysis* [IEA]. <https://www.iea.org/reports/norway-2022/executive-summary>
- IEA. (2025a). *Behavioural changes - energy system* [IEA]. <https://www.iea.org/energy-system/energy-efficiency-and-demand/behavioural-changes>
- IEA. (2025b). *Global critical minerals outlook 2025*. <https://iea.blob.core.windows.net/assets/ef5e9b70-3374-4caa-ba9d-19c72253bfc4/GlobalCriticalMineralsOutlook2025.pdf>
- IFAD. (2024). *The three types of biodiversity: Explained* [IFAD]. <https://www.ifad.org/en/w/explainers/the-three-types-of-biodiversity-explained>
- Impossible Metals. (2025a). *FAQS: Transport vessels* [Impossible metals]. <https://impossiblemetals.com/frequently-asked-questions/faqs-transport-vessels/>
- Impossible Metals. (2025b). *Home* [Impossible metals]. <https://impossiblemetals.com/>
- ISA. (2021). *The contribution of the international seabed authority to the achievement of the 2030 agenda for sustainable development*. [https://www.isa.org.jm/wp-content/uploads/2021/02/ISA\\_Contribution\\_to\\_the\\_SDGs\\_2021.pdf](https://www.isa.org.jm/wp-content/uploads/2021/02/ISA_Contribution_to_the_SDGs_2021.pdf)
- ISA. (2022). *Polymetallic nodules*. <https://www.isa.org.jm/wp-content/uploads/2022/06/eng7.pdf>
- ISA. (2025a). *Exploration contracts*. <https://www.isa.org.jm/exploration-contracts/>
- ISA. (2025b). *Frequently asked questions (FAQs) - what is the role of ISA?* <https://www.isa.org.jm/frequently-asked-questions-faqs/>
- ISA. (2025c). *The mining code*. <https://www.isa.org.jm/the-mining-code/>
- ISA. (2025d). *Statement on the US executive order: ‘unleashing america’s offshore critical minerals and resources’ - international seabed authority*. <https://www.isa.org.jm/news/statement-on-the-us-executive-order-unleashing-americas-offshore-critical-minerals-and-resources/>
- ISO. (2006). *ISO 14040:2006(en), environmental management — life cycle assessment — principles and framework*. <https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en>
- IUCN. (2024). *The impact of deep-sea mining on biodiversity, climate and human cultures* [https://www.iucn.nl/en/]. <https://www.iucn.nl/en/news/the-impact-of-deep-sea-mining-on-biodiversity-climate-and-human-cultures/>
- Jackson, J., & Chakraborty, A. (2025). *Why deep-seabed mining needs a moratorium* [Pew]. <https://pewtrsts.org/4kNqlid>
- Jaeckel, A., Harden-Davies, H., Amon, D. J., van der Grient, J., Hanich, Q., van Leeuwen, J., Niner, H. J., & Seto, K. (2023). *Deep seabed mining lacks social legitimacy* [Publisher: Nature Publishing Group]. *npj Ocean Sustainability*, 2(1), 1. <https://doi.org/10.1038/s44183-023-00009-7>

- JORC. (2024). *JORC code update*. <https://www.jorc.org/>
- JPI Oceans. (2022). *MiningImpact 2*. [https://www.jpi-oceans.eu/sites/jpi-oceans.eu/files/MI2\\_FinalReport\\_Publishable\\_web\\_2023.pdf](https://www.jpi-oceans.eu/sites/jpi-oceans.eu/files/MI2_FinalReport_Publishable_web_2023.pdf)
- JPI Oceans. (2024). *Third in a trilogy: New project selected to study ecological impacts of deep-sea mining*. <https://www.jpi-oceans.eu/en/third-trilogy-new-project-selected-study-ecological-impacts-deep-sea-mining>
- Kaikkonen, L., & Virtanen, E. A. (2022). Shallow-water mining undermines global sustainability goals [Publisher: Elsevier]. *Trends in Ecology & Evolution*, 37(11), 931–934. <https://doi.org/10.1016/j.tree.2022.08.001>
- Katona, S., Paulikas, D., Ali, S., Clarke, M., Ilves, E., Lovejoy, T. E., Madin, L. P., & Stone, G. S. (2023). Land and deep-sea mining: The challenges of comparing biodiversity impacts. *Biodiversity and Conservation*, 32(4), 1125–1164. <https://doi.org/10.1007/s10531-023-02558-2>
- Khan, Y. (2025). A miner goes bust, another goes solo as progress on u.n. seabed rules stalls. *Wall Street Journal*. <https://www.wsj.com/articles/a-miner-goes-bust-another-goes-solo-as-progress-on-u-n-seabed-rules-stalls-cba45638>
- Kirchain, R., Roth, R., Field, F. R., Muñoz-Royo, C., & Peacock, T. (2019). Economic model and system of payments. <https://www.isa.org.jm/wp-content/uploads/2022/06/paysysmodel-3jun.pdf>
- Knudsen, M. T., Hermansen, J. E., Cederberg, C., Herzog, F., Vale, J., Jeanneret, P., Sarthou, J.-P., Friedel, J. K., Balázs, K., Fjellstad, W., Kainz, M., Wolfrum, S., & Dennis, P. (2017). Characterization factors for land use impacts on biodiversity in life cycle assessment based on direct measures of plant species richness in european farmland in the ‘temperate broadleaf and mixed forest’ biome. *Science of The Total Environment*, 580, 358–366. <https://doi.org/10.1016/j.scitotenv.2016.11.172>
- Koschinsky, A., Heinrich, L., Boehnke, K., Cohrs, J. C., Markus, T., Shani, M., Singh, P., Smith Stegen, K., & Werner, W. (2018). Deep-sea mining: Interdisciplinary research on potential environmental, legal, economic, and societal implications. *Integrated Environmental Assessment and Management*, 14(6), 672–691. <https://doi.org/10.1002/ieam.4071>
- Levin, L. A., Wei, C.-L., Dunn, D. C., Amon, D. J., Ashford, O. S., Cheung, W. W. L., Colaço, A., Dominguez-Carrió, C., Escobar, E. G., Harden-Davies, H. R., Drazen, J. C., Ismail, K., Jones, D. O. B., Johnson, D. E., Le, J. T., Lejzerowicz, F., Mitarai, S., Morato, T., Mulsow, S., . . . Yasuhara, M. (2020). Climate change considerations are fundamental to management of deep-sea resource extraction. *Global Change Biology*, 26(9), 4664–4678. <https://doi.org/10.1111/gcb.15223>
- Lins, L., Zeppilli, D., Menot, L., Michel, L. N., Bonifácio, P., Brandt, M., Pape, E., Rossel, S., Uhlenkott, K., Macheriotou, L., Bezerra, T. N., Sánchez, N., Alfaro-Lucas, J. M., Martínez Arbizu, P., Kaiser, S., Murakami, C., & Vanreusel, A. (2021). Toward a reliable assessment of potential ecological impacts of deep-sea polymetallic nodule mining on abyssal infauna. *Limnology and Oceanography: Methods*, 19(9), 626–650. <https://doi.org/10.1002/lom3.10448>
- Liu, B., Wang, X., Zhang, X., Liu, J., Rong, L., & Ma, Y. (2024). Research status of deep-sea polymetallic nodule collection technology. *Journal of Marine Science and Engineering*, 12, 744. <https://doi.org/10.3390/jmse12050744>
- Loke marine minerals. (n.d.). *Deep sea minerals for the green transition* [Loke marine minerals]. <https://lokemm.com/>

- Ma, W., Schott, D., & Van Rhee, C. (2019). Numerical calculations of environmental impacts for deep sea mining activities. *Science of The Total Environment*, 652, 996–1012. <https://doi.org/10.1016/j.scitotenv.2018.10.267>
- Metal 3DP. (2024). *The ultimate cobalt powder guide for industry leaders*. <https://met3dp.sg/the-ultimate-cobalt-powder-guide-for-industry-leaders/>
- Metaxas, A., Anglin, C. D., Cross, A., Drazen, J., Haeckel, M., Mudd, G., Smith, C. R., Smith, S., Weaver, P. P. E., Sonter, L., Amon, D. J., Erskine, P. D., Levin, L. A., Lily, H., Maest, A. S., Mestre, N. C., Ramirez-Llodra, E., Sánchez, L. E., Sharma, R., . . . Tunnicliffe, V. (2024). Comparing environmental impacts of deep-seabed and land-based mining: A defensible framework. *Global Change Biology*, 30(5), e17334. <https://doi.org/10.1111/gcb.17334>
- MIDAS. (2017a). *Deep-sea mining: An introduction*. [https://www.oceanfdn.org/sites/default/files/MIDAS\\_brief\\_Introduction.compressed.pdf](https://www.oceanfdn.org/sites/default/files/MIDAS_brief_Introduction.compressed.pdf)
- MIDAS. (2017b). *Managing impacts of deep-sea resource exploitation*. <https://cordis.europa.eu/project/id/603418/reporting>
- Miller, K. A., Brigden, K., Santillo, D., Currie, D., Johnston, P., & Thompson, K. F. (2021). Challenging the need for deep seabed mining from the perspective of metal demand, biodiversity, ecosystems services, and benefit sharing [Publisher: Frontiers]. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.706161>
- Mononen, T., Kivinen, S., Kotilainen, J. M., & Leino, J. (2022). Social and environmental impacts of mining activities in the EU. [https://www.europarl.europa.eu/RegData/etudes/STUD/2022/729156/IPOL\\_STU\(2022\)729156\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/STUD/2022/729156/IPOL_STU(2022)729156_EN.pdf)
- Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B., & Worm, B. (2011). How many species are there on earth and in the ocean? *PLoS Biology*, 9(8), e1001127. <https://doi.org/10.1371/journal.pbio.1001127>
- Mphaga, K. V., Utembe, W., Mbonane, T. P., & Rathebe, P. C. (2024). Indoor radon exposure: A systematic review of radon-induced health risks and evidence quality using GRADE approach. *Heliyon*, 10(23), e40439. <https://doi.org/10.1016/j.heliyon.2024.e40439>
- NettZero. (2024). *Understanding 16 impact categories in life cycle assessment* [Section: Carbon Neutrality]. <https://nettzero.com.au/blog/lca-impact-categories>
- NIOZ. (2024). *Unexpected biodiversity on the ocean floor*. <https://www.nioz.nl/en/news/unexpected-biodiversity-on-the-ocean-floor>
- NOAA. (2024). *Maritime zones and boundaries | national oceanic and atmospheric administration*. <https://www.noaa.gov/maritime-zones-and-boundaries>
- NORI. (2022). *Collector test study*. [https://metals.co/wp-content/uploads/dlm\\_uploads/2022/12/NORI-D-Collector-Test-EIS-Final-Executive-Summary-and-Table-of-Contents.pdf](https://metals.co/wp-content/uploads/dlm_uploads/2022/12/NORI-D-Collector-Test-EIS-Final-Executive-Summary-and-Table-of-Contents.pdf)
- Ochromowicz, K., Aasly, K., & Kowalczyk, P. B. (2021). Recent advancements in metallurgical processing of marine minerals [Number: 12 Publisher: Multidisciplinary Digital Publishing Institute]. *Minerals*, 11(12), 1437. <https://doi.org/10.3390/min11121437>
- Patel, R. (2021). *Obscure impacts demystified: Acidification* [PRé sustainability]. <https://pre-sustainability.com/articles/obscure-impacts-demystified-acidification/>

- Paulikas, D., Katona, S., Ilves, E., & Ali, S. H. (2020a). Life cycle climate change impacts of producing battery metals from land ores versus deep-sea polymetallic nodules. *Journal of Cleaner Production*, 275, 123822. <https://doi.org/10.1016/j.jclepro.2020.123822>
- Paulikas, D., Katona, S., Ilves, E., Stone, G., & O'Sullivan, A. (2020b). Where should metals for the green transition come from? <https://doi.org/10.13140/RG.2.2.21346.66242>
- Pickens, C., Lily, H., Harrould-Kolieb, E., Blanchard, C., & Chakraborty, A. (2024). From what-if to what-now: Status of the deep-sea mining regulations and underlying drivers for outstanding issues. *Marine Policy*, 169, 105967. <https://doi.org/10.1016/j.marpol.2023.105967>
- Planet Tracker. (2023). *The sky high cost of deep sea mining*. <https://planet-tracker.org/wp-content/uploads/2023/06/Deep-Sea-Mining.pdf>
- Planet Tracker. (2024). *Race to the bottom*. <https://planet-tracker.org/wp-content/uploads/2024/11/Race-to-the-Bottom.pdf>
- Préat, N., Lefaible, N., Alvarenga, R. A., Taelman, S. E., & Dewulf, J. (2021). Development of a life cycle impact assessment framework accounting for biodiversity in deep seafloor ecosystems: A case study on the clarion clipperton fracture zone. *Science of The Total Environment*, 770, 144747. <https://doi.org/10.1016/j.scitotenv.2020.144747>
- RIVM. (2016). *ReCiPe 2016*. <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf>
- RIVM. (2025). *Air quality*. <https://www.rivm.nl/en/climate-change-and-health/air-quality>
- Royal IHC. (2025). *Mining equipment* | royal IHC. <https://www.royalihc.com/mining/mining-equipment>
- Sarac, D. (n.d.). *Photochemical oxidation* [Water revolution foundation]. <https://waterrevolutionfoundation.org/verified-solutions/photochemical-oxidation/>
- Schott, D., De Hoog, E., Van Wijk, J., & Helmons, R. (2024). Handling of bulk solids in a marine environment, from seabed to shore. In R. Sharma (Ed.), *Deep-sea mining and the water column* (pp. 91–127). Springer Nature Switzerland. [https://doi.org/10.1007/978-3-031-59060-3\\_4](https://doi.org/10.1007/978-3-031-59060-3_4)
- Sharma, R. (2015). Environmental issues of deep-sea mining. *Procedia Earth and Planetary Science*, 11, 204–211. <https://doi.org/10.1016/j.proeps.2015.06.026>
- Sharma, R., & Smith, S. (2019). Deep-sea mining and the environment: An introduction. In R. Sharma (Ed.), *Environmental issues of deep-sea mining: Impacts, consequences and policy perspectives* (pp. 3–22). Springer International Publishing. [https://doi.org/10.1007/978-3-030-12696-4\\_1](https://doi.org/10.1007/978-3-030-12696-4_1)
- Shirayama, Y., Itoh, H., & Fukushima, T. (2017). Recent developments in environmental impact assessment with regard to mining of deep-sea mineral resources. In R. Sharma (Ed.), *Deep-sea mining: Resource potential, technical and environmental considerations* (pp. 445–463). Springer International Publishing. [https://doi.org/10.1007/978-3-319-52557-0\\_15](https://doi.org/10.1007/978-3-319-52557-0_15)
- SINTEF. (2022). *The future is circular - circular economy and critical minerals for the green transition* [Accepted: 2022-11-16T08:59:58Z Journal Abbreviation: The Future is Circular - Circular Economy and Critical Minerals for the Green Transition Publication Title: 71]. <https://sintef.brage.unit.no/sintef-xmlui/handle/11250/3032049>
- SMM. (2025a). *Cobalt powder price today*. <https://www.metal.com/en/prices/201102250186>
- SMM. (2025b). *SiMn alloy(6517) - south price today | historical price charts of SiMn alloy(6517) - south - shanghai metal market*. <https://www.metal.com/en/prices/201205090002>

- SMM. (2025c). *SMM #1 nickel price today*. <https://www.metal.com/Nickel/201102250239>
- SMM. (2025d). *SMM 1# copper cathode price today*. <https://www.metal.com/Copper/201102250376>
- Sustainability Directory. (2025). *Enforcement challenges in deep sea mining zones* [Prism]. <https://prism.sustainability-directory.com/scenario/enforcement-challenges-in-deep-sea-mining-zones-2/>
- The Metals Company. (2021). *Prospectus: TMC the metals company*. [https://www.sec.gov/Archives/edgar/data/1798562/000121390021054189/f424b31021\\_tmcinc.htm](https://www.sec.gov/Archives/edgar/data/1798562/000121390021054189/f424b31021_tmcinc.htm)
- The Metals Company. (2022). *NORI and allseas lift over 3,000 tonnes of polymetallic nodules to surface from planet's largest deposit of battery metals, as leading scientists and marine experts continue gathering environmental data*. <https://investors.metals.co/news-releases/news-release-details/nori-and-allseas-lift-over-3000-tonnes-polymetallic-nodules/>
- The Metals Company. (2023a). *Lifecycle assessment by benchmark shows TMC's NORI-d nodule project could outperform land-based routes of producing nickel, copper and cobalt in almost every impact category analyzed*. <https://investors.metals.co/news-releases/news-release-details/lifecycle-assessment-benchmark-shows-tmcs-nori-d-nodule-project/>
- The Metals Company. (2023b). *TMC enters into MOU with leading nickel processor PAMCO to evaluate the processing of polymetallic nodules into battery metal feedstocks*. <https://investors.metals.co/news-releases/news-release-details/tmc-enters-mou-leading-nickel-processor-pamco-evaluate/>
- The Metals Company. (2024a). *Company* [The metals company]. <https://metals.co/company/>
- The Metals Company. (2024b). *Lifecycle* [The metals company]. <https://metals.co/lifecycle/>
- The Metals Company. (2024c). *Nodules* [The metals company]. <https://metals.co/nodules/>
- The Metals Company. (2024d). *TMC announces june 27, 2025 submission date for subsidiary NORI's ISA application, and expanded company strategy | the metals company*. <https://investors.metals.co/news-releases/news-release-details/tmc-announces-june-27-2025-submission-date-subsiary-noris-isa/>
- The Metals Company. (2025a). *The metals company to apply for permits under existing u.s. mining code for deep-sea minerals in the high seas in second quarter of 2025*. <https://investors.metals.co/news-releases/news-release-details/metals-company-apply-permits-under-existing-us-mining-code-deep/>
- The Metals Company. (2025b). *TMC welcomes u.s. executive order to expedite permitting and evaluate offtake of critical minerals from nodules in the high seas*. <https://investors.metals.co/news-releases/news-release-details/tmc-welcomes-us-executive-order-expedite-permitting-and-evaluate/>
- The Metals Company. (2025c). *World first: TMC and PAMCO achieve a new nodule processing milestone, unlocking critical energy & steelmaking materials at existing facilities | the metals company*. <https://investors.metals.co/news-releases/news-release-details/world-first-tmc-and-pamco-achieve-new-nodule-processing/>
- TNO. (2023). *No energy transition without raw materials transition* [Tno.nl/en]. <https://www.tno.nl/en/newsroom/insights/2023/08/energy-transition-without-raw-materials/>
- Trump, D. (2025). *Unleashing america's offshore critical minerals and resources* [The white house]. <https://www.whitehouse.gov/presidential-actions/2025/04/unleashing-americas-offshore-critical-minerals-and-resources/>

- TU Delft. (2024). *Delftse onderzoekers zetten volgende stap naar betere batterijen met breed beschikbare materialen op basis van Na-ionen* [TU Delft]. <https://www.tudelft.nl/2024/tnw/delftse-onderzoekers-zetten-volgende-stap-naar-betere-batterijen-met-breed-beschikbare-materialen-op-basis-van-na-ionen>
- UNCLOS. (1982). *United nations convention on the law of the sea*. [https://www.un.org/depts/los/convention\\_agreements/texts/unclos/UNCLOS-TOC.htm](https://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm)
- US EPA. (2025a). *Basic ozone layer science*. <https://www.epa.gov/ozone-layer-protection/basic-ozone-layer-science>
- US EPA, O. (2025b). *Ecological risk assessment*. <https://www.epa.gov/risk/ecological-risk-assessment>
- USGS. (2025). *Mineral commodity summaries 2025* (No. 2025) (ISBN: 9781411345959 Publication Title: Mineral Commodity Summaries). U.S. Geological Survey. <https://doi.org/10.3133/mcs2025>
- USS. (2020). Blast furnace sludge. (26). <https://www.ussteel.com/documents/40705/43680/Blast+Furnace+Sludge+SDS.pdf/98a68b3d-3d8e-d8a7-7857-c4b4775778ac?t=1603230621769>
- Van der Voet, E., Lifset, R. J., & Luo, L. (2010). Life-cycle assessment of biofuels, convergence and divergence. *Biofuels*, 1(3), 435–449. <https://doi.org/10.4155/bfs.10.19>
- Van der Voet, E., Van Oorschot, J., Verhagen, T., Van Oers, L., Van Straalen, V., Tunn, V., Kersten, K., & Delahaye, R. (2025). The urban mine of the netherlands: The material basis for a circular economy. *Journal of Industrial Ecology*, 29(3), 967–981. <https://doi.org/10.1111/jiec.70030>
- Verma, M. (2023). Deep sea mining and the circular economy: Opportunities and challenges. 7, 21–27.
- Vivoda, V. (2024). Uncharted depths: Navigating the energy security potential of deep-sea mining. *Journal of Environmental Management*, 369, 122343. <https://doi.org/10.1016/j.jenvman.2024.122343>
- Wang, Q., Zhou, D., Zhao, C., Wang, J., Guo, H., Wang, L., Yao, Z., Wong, D., Schuck, G., Bai, X., Lu, J., & Wagemaker, M. (2024). Fast-charge high-voltage layered cathodes for sodium-ion batteries [Publisher: Nature Publishing Group]. *Nature Sustainability*, 7(3), 338–347. <https://doi.org/10.1038/s41893-024-01266-1>
- Weaver, P., Aguzzi, J., Boschen-Rose, R., Colaço, A., De Stigter, H., Gollner, S., Haeckel, M., Hauton, C., Helmons, R., Jones, D., Lily, H., Mestre, N., Mohn, C., & Thomsen, L. (2022). Assessing plume impacts caused by polymetallic nodule mining vehicles. *Marine Policy*, 139, 105011. <https://doi.org/10.1016/j.marpol.2022.105011>
- Weiskopf, S. R., Isbell, F., Arce-Plata, M. I., Di Marco, M., Harfoot, M., Johnson, J., Lerman, S. B., Miller, B. W., Morelli, T. L., Mori, A. S., Weng, E., & Ferrier, S. (2024). Biodiversity loss reduces global terrestrial carbon storage [Publisher: Nature Publishing Group]. *Nature Communications*, 15(1), 4354. <https://doi.org/10.1038/s41467-024-47872-7>
- WindEurope. (2024). *Wind energy in europe: 2023 statistics and the outlook for 2024-2030* [WindEurope]. <https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2023-statistics-and-the-outlook-for-2024-2030/>
- Zeb Nickel Corp. (2025). *Why nickel: Class 1 vs. class 2 nickel*. <https://zebnickel.com/why-nickel/>
- Zhang, Q., Chen, X., Luan, L., Sha, F., & Liu, X. (2025). Technology and equipment of deep-sea mining: State of the art and perspectives. *Earth Energy Science*, 1(1), 65–84. <https://doi.org/10.1016/j.ees.2024.08.002>

# Appendix A: ReCiPe 2016 Categories

**Table A.1:** ReCiPe 2016 Midpoint Impact Categories with Units and Definitions, adapted from NetZero (2024).

<b>Impact Category</b>	<b>Unit</b>	<b>Definition</b>
Acidification	kg SO <sub>2</sub> -Eq	Emissions that can form acid rains and harm water, soil, and ecosystems.
Climate Change	kg CO <sub>2</sub> -Eq	Emissions of greenhouse gases that cause global warming and climate change.
Ecotoxicity: Freshwater	kg 1,4-DCB-Eq	Toxic emissions of chemicals to freshwater ecosystems and aquatic life.
Ecotoxicity: Marine	kg 1,4-DCB-Eq	Toxic emissions of chemicals to marine ecosystems and aquatic life.
Ecotoxicity: Terrestrial	kg 1,4-DCB-Eq	Toxic effects of chemicals on terrestrial ecosystems and terrestrial life .
Energy Resources	kg oil-Eq	Depletion of natural fossil energy resources.
Eutrophication: Freshwater	kg P-Eq	Nutrient enrichment leading to excessive algae growth in freshwater ecosystems.
Eutrophication: Marine	kg N-Eq	Nutrient enrichment causing harmful algal blooms and oxygen depletion in marine ecosystems.
Human Toxicity: Carcinogenic	kg 1,4-DCB-Eq	Toxic emissions of carcinogenic substances that lead to human health impacts.
Human Toxicity: Non-Carcinogenic	kg 1,4-DCB-Eq	Toxic emissions of non-carcinogenic substances that lead to human health impacts.
Ionising Radiation	kBq Co-60-Eq	Effects of ionising radiation on human health and ecosystems.
Land Use	m <sup>2</sup> -a crop-Eq	Occupation and time-integrated transformation of land, impacting biodiversity and ecosystems.
Material Resources	kg Cu-Eq	Depletion of mineral and metal resources due to extraction and consumption.
Ozone Depletion	kg CFC-11-Eq	Emissions on stratospheric ozone layer depletion, increasing UV radiation exposure.
Particulate Matter Formation	kg PM <sub>2,5</sub> -Eq	Emissions to air of fine particulate matter affecting human health.
Photochemical Oxidant Formation: Human Health	kg NO <sub>x</sub> -Eq	Formation of ground-level oxidants and other pollutants harming human respiratory health (also called "smog").
Photochemical Oxidant Formation: Terrestrial Ecosystems	kg NO <sub>x</sub> -Eq	Formation of ground-level oxidants and other pollutants causing damage to vegetation (also called "smog").
Water Use	m <sup>3</sup>	Consumption and depletion of freshwater resources.

# Appendix B: Comparative Analysis

## B.1. Goal & Scope

	1	2	3	4	5
	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Paulikas, Katona, Ilves, and Ali	Benchmark Minerals	Alvarange et al.	Fritz et al.
<b>Goal definition</b>	Compare the environmental, social, and economic impacts of producing battery cathode precursors and copper from land-based ores and from polymetallic nodules from the deep-sea in the CCZ.	Assess the climate change impacts of producing four metals that are needed for 1 billion EVs for the period 2017 to 2047, from deep-sea polymetallic nodules compared to land ores from conventional and green land-mining.	Inform TMC and stakeholders of the potential environmental impacts of the production of Ni/Cu/Co matte, manganese silicate, cobalt sulphate, nickel sulphate, and copper cathode materials from polymetallic nodules mined in the NORI-D area, compared to current terrestrial mining.	Analyze the environmental performance of mining deep-sea polymetallic nodules in the CCZ compared to terrestrial mining with equivalent production.	Analyze the climate change impact caused by the production of Ni, Cu, Co, and FeMn from nodules from the CCZ compared to the existing land-based alternative.
<b>Geographical scope deep-sea mining</b>	<b>Extraction:</b> Pacific Ocean's Clarion Clipperton Zone (CCZ) <b>Processing:</b> Exact location is unspecified, but assumed to be close to a port, running hydropower, and end-markets.	<b>Extraction:</b> Pacific Ocean's Clarion Clipperton Zone (CCZ) <b>Processing:</b> Exact location is unspecified, but assumed to be close to a port, running hydropower, and end-markets.	<b>Extraction:</b> Pacific Ocean's Clarion Clipperton Zone (CCZ), NORI-D area <b>Processing:</b> Texas (baseline model)	<b>Extraction:</b> Pacific Ocean's Clarion Clipperton Zone (CCZ) <b>Processing:</b> "Scenario A" and "Scenario B" (refer to real countries, but the authors keep these confidential)	<b>Extraction:</b> Pacific Ocean's Clarion Clipperton Zone (CCZ) <b>Processing:</b> Port Lázaro Cárdenas, Mexico
<b>Geographical scope land-based mining</b>	Global values, focusing on production paths that are most likely for producing EV batteries in the future.	Global values, focusing on production paths that are most likely for producing EV batteries in the future.	<b>Extraction:</b> Australia <b>Refining:</b> China	Global averages	Finland (Kevitsa sulfide nickel project) & Australia (Murrin Murrin nickel-cobalt project and Woodie Woodie ferromanganese project)
<b>Temporal scope</b>	Impacts from 2017 to 2047 with 2 future scenarios for land-based mining and 1 fixed scenario for deep-sea mining. Secondary data from 2010 (Ecoinvent v2.2) and 2018 (Ecoinvent v3.5)	Impacts from 2017 to 2047 with 2 future scenarios for land-based mining and 1 fixed scenario for deep-sea mining. Secondary data from 2010 (Ecoinvent v2.2) and 2018 (Ecoinvent v3.5)	Data is from 2022 (from TMC & Benchmark) and secondary data is from 2021 (Ecoinvent v3.8) and 2018 (GREET).	<b>DSM:</b> Future large-scale production (prospective). Secondary data from 2018 (Ecoinvent v3.5) <b>Land-based:</b> 2013 (Cu), 2011 (Ni), 2012 (Co), and 2018 (GaBi v8.7).	Data sources span from 1977 to 2021 and secondary data from Ecoinvent is from 2020 (ecoinvent v3.7.1)
<b>Technological scope deep-sea alternative</b>	The system for collecting, processing, and refining polymetallic nodules is inline with the system of TMC. This includes the collection technology of Allseas, the riser technology of Deep Reach Technologies, and the processing technologies of Hatch.	The system for collecting, processing, and refining polymetallic nodules is inline with the system of TMC. This includes the collection technology of Allseas, the riser technology of Deep Reach Technologies, and the processing technologies of Hatch.	Technologies used in the TMC NORI-D project.	Commercial version of the nodule collector developed by GSR.	The system for collecting, processing, and refining polymetallic nodules is based on studies of Heinrich et al. (2020) and Kirchain et al. (2019) and the basic metallurgical processes are based on the of Dames & Moore and EIC Corporation (1977).
<b>Technological scope land-based alternative</b>	Conventional mining and refining systems as modeled in Ecoinvent v2.2.	Conventional mining and refining systems as modeled in Ecoinvent v2.2.	Present-day (2022) averages of technology systems.	Most reliable and available terrestrial mining processes, representing global averages.	Conventional mining and refining systems as used in the Kevitsa, Murrin Murrin, and Woodie Woodie projects and as modeled in Ecoinvent v3.7.1.
<b>Function</b>	Producing metals ( <b>Ni, Cu, Co, Mn</b> ) needed for EVs.  (EV is assumed to be a Tesla Model 3 that requires a 75 kWh NMC 811 lithium-ion battery cathode and copper connectors and harness. Therefore, one EV requires 56.2 kg of Ni, 85 kg of Cu, 7.05 kg of Co, and 6.6 kg of Mn)	Producing metals ( <b>Ni, Cu, Co, Mn</b> ) needed for EVs.  (EV is assumed to be a Tesla Model 3 that requires a 75 kWh NMC 811 lithium-ion battery cathode and copper connectors and harness. Therefore, one EV requires 56.2 kg of Ni, 85 kg of Cu, 7.05 kg of Co, and 6.6 kg of Mn)	Producing <b>Ni, Cu, and Co</b> .	Delivery of commodities ( <b>Ni, Cu, Co, FeMn</b> ) to the market.	Providing metals ( <b>Ni, Cu, Co, FeMn</b> ) to the industry.

<b>Functional unit</b>	Producing metals (Ni, Cu, Co, Mn) needed for 1 billion EVs by 2047.	Producing metals (Ni, Cu, Co, Mn) needed for 1 billion EVs by 2047.	Producing: A) 1 kg of Ni/Cu/Co matte, B) 1 kg of Ni in Nickel sulphate, C) 1 kg of Co in Cobalt sulphate, D) 1 kg of Cu cathode.	Delivering 12.8 kg of Ni, 10.5 kg of Cu, 2.3 kg of Co, and 311.3 kg of FeMn to the market.	Providing 15.3 gram of Ni, 11.7 gram of Cu, 2.2 gram of Co, and 338 g of FeMn to the industry.
<b>Alternatives</b>	<b>Alternative 1:</b> Metals from deep-sea mined polymetallic nodules. <b>Alternative 2:</b> Metals from land-based mined ores.	<b>Alternative 1:</b> Metals from deep-sea mined polymetallic nodules. <b>Alternative 2:</b> Metals from land-based mined ores.	<b>Alternative 1:</b> Metals from TMC's NORI-D polymetallic nodule collection. <b>Alternative 2:</b> Metals from dominant terrestrial mining routes.	<b>Alternative 1:</b> Commodities from mining deep-sea polymetallic nodules. <b>Alternative 2:</b> Commodities from terrestrial-mining.	<b>Alternative 1:</b> Metals from mining deep-sea polymetallic nodules. <b>Alternative 2:</b> Metals from land-based mining operations.
<b>Reference flows</b>	<b>1:</b> Metals for 1 billion EVs produced from deep-sea mined polymetallic nodules by 2047. <b>2:</b> Metals for 1 billion EVs produced from land-based mined ores by 2047.	<b>1:</b> Metals for 1 billion EVs produced from deep-sea mined polymetallic nodules by 2047. <b>2:</b> Metals for 1 billion EVs produced from land-based mined ores by 2047.	<b>A1:</b> 1 kg of Ni/Cu/Co matte produced from TMC's NORI-D polymetallic nodule collection. <b>A2:</b> 1 kg of Ni/Cu/Co matte produced from dominant terrestrial mining routes. <b>B1:</b> 1 kg of Ni in Nickel sulphate produced from TMC's NORI-D polymetallic nodule collection. <b>B2:</b> 1 kg of Ni in Nickel sulphate produced from dominant terrestrial mining routes. <b>C1:</b> 1 kg of Co in Cobalt sulphate produced from TMC's NORI-D polymetallic nodule collection. <b>C2:</b> 1 kg of Co in Cobalt sulphate produced from dominant terrestrial mining routes. <b>D1:</b> 1 kg of Cu cathode produced from TMC's NORI-D polymetallic nodule collection. <b>D2:</b> 1 kg of Cu cathode produced from dominant terrestrial mining routes.	<b>1:</b> One unit of commodities (12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn) from deep-sea mining of polymetallic nodules delivered to the market. <b>2:</b> One unit of commodities (12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn) from terrestrial-mining delivered to the market.	<b>1:</b> One unit of metals (15.3 g Ni, 11.7 g Cu, 2.2 g Co, 338 g FeMn) from deep-sea mining of polymetallic nodules provided to the industry <b>2:</b> One unit of metals (15.3 g Ni, 11.7 g Cu, 2.2 g Co, 338 g FeMn) from land-based mining sources provided to the industry.
<b>System boundary</b>	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate
<b>Further comments</b>	This LCA study considers two land-ore supply scenarios: <b>Baseline land-ores scenario:</b> - Economic growth is the largest driver. - Global electricity mix transitions slowly to renewables. - Negative impact of ore-grade decrease in copper and nickel is dominating. <b>Green land-ores scenario.</b> - Focus on Sustainable Development Goals - Significant transition to renewables. - Material reduction, but still partly offset by impact of ore-grade decrease.	This LCA study considers two land-ore supply scenarios: <b>Baseline land-ores scenario:</b> - Economic growth is the largest driver. - Global electricity mix transitions slowly to renewables. - Negative impact of ore-grade decrease in copper and nickel is dominating. <b>Green land-ores scenario.</b> - Focus on Sustainable Development Goals - Significant transition to renewables. - Material reduction, but still partly offset by impact of ore-grade decrease.		There are 2 scenarios for the processing location: <b>Scenario A:</b> - Distance between nodules site and harbor is 4010 km - Electricity mix = 85% hydropower, 6% natural gas, 4% coal&lignite, 2% wind, and 3% others. <b>Scenario B:</b> - Distance between nodules site and harbor is 2000 km - Electricity mix = 55% natural gas, 15% hydropower, 13% coal&lignite, 10% oil, 4% nuclear, and 3% others.  The scenarios refer to real countries, but the authors keep these confidential.	



Technologies/Methods in land-based mining model	<p><b>Nickel sulphate route 1 (pyro)</b> : Underground mining &gt; comminution &gt; froth flotation &gt; drying &gt; smelting &gt; hydrogen-sulphide reduction &gt; crystallization</p> <p><b>Nickel sulphate route 2 (hydro)</b>: Open-pit mining &gt; sulfuric acid leaching/HPAL &gt; solvent extraction &gt; electrowinning &gt; crystallization</p> <p><b>Cobalt sulphate route 1 (hydro)</b> : Underground &amp; open-pit mining &gt; comminution &gt; froth flotation &gt; roasting &gt; sulfuric acid leaching &gt; solvent extraction &amp; stripping &gt; precipitation &gt; reaction with MgO &gt; leaching &amp; solvent extraction &gt; evaporation &gt; crystallization &gt; filtration &gt; drying</p> <p><b>Cobalt sulphate route 2 (hydro)</b>: Underground &amp; open-pit mining &gt; comminution &gt; froth flotation &gt; roasting &gt; sulfuric acid leaching &gt; solvent extraction &amp; stripping &gt; precipitation &gt; reaction with MgO &gt; leaching &amp; solvent extraction &gt; electrowinning &gt; crystallization</p> <p><b>Manganese sulphate route 1 (hydro)</b>: open-pit mining &gt; leaching &gt; neutralization &gt; filtration &gt; vulcanization &gt; absorption &amp; standing &gt; electrolysis</p> <p><b>Manganese sulphate route 2 (hydro)</b> : Open-pit mining &gt; dissolving in sulfuric acid &gt; oxidation &gt; neutralization &gt; precipitation &gt; filtration &gt; electrolysis</p> <p><b>Manganese sulphate route 3 &amp; 4 (pyro)</b> : Open-pit (70%) &amp; underground (30%) mining &gt; comminution &gt; screening &gt; reaction with sulfuric acid</p> <p><b>Copper cathode route 1 (hydro)</b>: Open-pit &amp; underground mining &gt; leaching &gt; solvent extraction &gt; electrowinning</p> <p><b>Copper cathode route 2 (pyro)</b>: Open-pit mining &gt; smelting &gt; drying &gt; roasting &gt; cooling &amp; electrorefining</p>	<p><b>Conventional processing technology</b>: flash furnace &amp; Pierce-Smith converters</p>	n/a	<p><b>Excavation</b> : Open-pit mining</p> <p><b>Pre-processing</b>: Comminution</p> <p><b>Transport</b>: Ship &amp; Truck (Woodie Woodie), Rail transport (Kevitsa)</p> <p><b>Processing</b>: Sintering &amp; smelting (Woodie Woodie), Hydrometallurgical plant (Murrin Murrin), Harjavalta smelter (Kevitsa)</p>
Cut-offs	<ul style="list-style-type: none"> <li>- Manufacture</li> <li>- Usage</li> <li>- Disposal</li> <li>- Recycling</li> </ul>	<ul style="list-style-type: none"> <li>- Packaging of the finished product</li> <li>- Transportation after packaging</li> <li>- Usage</li> <li>- Waste &amp; disposal</li> <li>- Recycling</li> </ul>	n/a	- Capital goods and infrastructure (unless listed in Ecoinvent)
Data sources deep-sea alternative	<p><b>Foreground processes:</b> Data is based on the operating concept of TMC, with use of CCZ resource statements (NI-43-101 compliant), pilot studies, engineering models, market forecasts from CRU International, analysis from ocean and metal production experts, resource surveys, engineering, scientific, and economic (AMC) consultancy, and literature review.</p> <p><b>Background processes:</b> Ecoinvent v2.2 (where data was not available, Ecoinvent v3.5 was used)</p>	<p><b>Foreground processes:</b> Primary data from the estimated yearly production processes of TMC.</p> <p><b>Background processes:</b> Ecoinvent database v3.8</p>	<p><b>Foreground processes:</b> Calculations based on proprietary and confidential engineering models of Global Sea Mineral Resources (GSR). Authors stated that they used confidential industry data that can not be evaluated.</p> <p><b>Background processes:</b> Ecoinvent database v3.5</p>	<p><b>Foreground processes:</b> Foreground system is based on the studies of Heinrich et al. (2020) and Kirchain et al. (2019) and the study of Dames &amp; Moore and EIC Corporation (1977) is used for the basic metallurgical processes.</p> <p><b>Background processes:</b> Ecoinvent database v.3.7.1</p>
Data sources land-mining alternative	<p>Published literature with adjustments for energy-efficiency improvements, ore-grade declines, and decarbonization dynamics of the electricity grid (for the year 2047).</p>	<p><b>Foreground processes:</b> Primary data from experts in the cobalt and nickel industry (chemical engineers). For cobalt mining, complementary data is used from GREET2018.</p> <p><b>Background processes:</b> Ecoinvent database v3.8</p>	<p>Generic data provided by metal commodity associations (for Ni, Cu, Co) and Gabi v8.7 database (for FeMn)</p> <p><b>Ni</b>: data from Nickel Institute. Global average production for the year 2011, covers 40% of world production</p> <p><b>Cu</b>: data from Copper Alliance. Average production for the year 2013, covers 21% of world population</p> <p><b>Co</b>: data from Cobalt Institute. Average production for the year 2012, covers 30% of world production</p> <p><b>FeMn</b>: Gabi dataset for processes in South Africa, covers 30% of production.</p>	<p><b>Foreground Woodie Woodie:</b></p> <ul style="list-style-type: none"> <li>- Excavation = Dataset of Classen et al. (2009), Ecoinvent v3.8.</li> <li>- Comminution = Data from publication Woodie Woodie mine (2010-2011).</li> <li>- Metallurgy = Datasets from International Manganese Institute (2014), reference year of data is 2010.</li> </ul> <p><b>Foreground Murrin Murrin:</b></p> <ul style="list-style-type: none"> <li>- Extraction from nature = Dataset from Nickel Institute of Boonzaier (2020), with reference year 2017.</li> <li>- Comminution = Data from Dames &amp; Moore (1996).</li> <li>- Metallurgy = Data from technical feasibility study Dames &amp; Moore (1996).</li> </ul> <p><b>Foreground Kevitsa :</b></p> <ul style="list-style-type: none"> <li>- Extraction from nature = Data from Skarn Associates Limited (2020), reference year of data is 2018</li> <li>- Comminution = Data from publications (Gray et al. 2016, Lehto et al., 2016)</li> <li>- Metallurgy = Finnish Environmental Institute Riekkola-Vanhanen (1999), reference year 1997-1998.</li> </ul> <p><b>Background processes:</b> Ecoinvent database v3.7.1.</p>
Software	Simapro	Simapro (v 9.4.0.2)	Simapro (v9.0)	Umberto 11
Multifunctionality & allocation of deep-sea alternative	<p><u>Three allocation groups:</u></p> <ol style="list-style-type: none"> <li>1. Nodule collection, transport, and pyrometallurgical processing = <b>Economic allocation</b></li> <li>2. Coal-based reduction = <b>Physical allocation</b></li> <li>3. Hydrometallurgical refining of a polymetallic matte = <b>Economic Allocation</b></li> </ol> <p>Output by economic allocation: 50% Ni, 13% Co, 22% Mn, 14% Cu</p>	<p><b>Physical allocation</b> : for pyrometallurgical process</p> <p><b>Economic allocation</b>: for hydrometallurgical processing/refining</p> <p><b>System expansion</b>: for by-product ammonium sulphate and converter slag.</p>	<ul style="list-style-type: none"> <li>- Substitution approach</li> <li>- By-products with low market values (e.g. Gypsum) are assumed to be burden-free, so no allocation.</li> </ul>	Economic allocation

Multifunctionality & allocation of land-based alternative	Economic allocation	Economic allocation	n/a	Economic allocation
<b>Important assumptions</b>	<p>Transport of the deep-sea alternative is by ship, because assumed is that the processing plant is close to the port.</p> <p>Of the total energy for processing and refining the nodules, 35% is natural gas, 34% is coal, 16% is hydropower for electricity, 15% comes from material inputs such as sulfuric acid, and 5% is from offshore operations.</p> <p>The electricity for processing and refining the nodules is 100% from hydropower.</p> <p>The smelting process is conducted with an electric furnace.</p> <p>The nodule system is a "planned project scenario" with the best practice without any waste or tailings.</p> <p>The electricity used in the land-mining alternative comes from the global electricity mix, which includes 25% renewables in 2050 in the baseline scenario and 64% renewables in 2050 in the green land-ores scenario</p>	<p>Lázaro Cárdenas, Mexico, is assumed as location for the port that is used for transshipment from the collection site to the processing site (Texas).</p> <p>TMC committed to 100% renewable electricity for processing the nodules. Assumed is 100% wind energy for the electricity for processing.</p> <p>The smelting process is conducted with an electric furnace.</p> <p>The electricity for the conventional land-based mining alternative comes from the carbon intensive Australian electricity mix.</p>	<p>The electrical energy use of the offshore pre-processing is based on the power demand of the separation processes, and the hydraulic power needed to return the water and sediment to the water column.</p> <p>Capacity of the transshipment system is based on the expected duration of the process, and the electrical power use is determined by the operational and physical parameters.</p> <p>Shipment to onshore take place on Panamax bulk carriers with their usual characteristics on capacity, speed, sailing and discharge times in port. With this, the number of bulk carriers and the amount of HFO consumption were estimated.</p> <p>The total power used for the communiution process is 4.1 MW.</p> <p>Scenario A has an electricity mix that is mainly composed of hydropower (85%) and Scenario B has a mix that mainly consists of natural gas (55%).</p> <p>The smelting process is conducted with a submerged arc furnace (SAF) (electric furnace).</p> <p>The electricity use of the land-based mining alternative comes from anticipated electricity mixes of 2015-2050.</p>	<p>The processing plant is located at the closest port to the CCZ (Lázaro Cárdenas, Mexico). Therefore, the only horizontal transport that is assumed is by vessel, not by train or truck on land.</p> <p>The electricity for processing the nodules comes from the Mexican grid mix, which includes more than 50% fossil energy.</p> <p>The smelting process is conducted with an electric furnace.</p> <p>The electricity used for the land-based ores of the Woodie Woodie project comes from the Chinese electricity mix, which is dominated by fossil fuels.</p> <p>The electricity used for the land-based ores of the Kevitsa projects comes from the Finnish electricity mix, which is dominated by hydropower.</p> <p>The electricity used for the land-based ores of the Murrin Murrin project is generated on their site by burning natural gas and sulfur.</p> <p>--&gt; The BGR selected these 3 land mines, because they best match the nodules as comparison and these projects are established in the market and considered economically viable.</p> <p>As explained in the detailed final report, the fate of the water in the nodules is neglected in the deep-sea model. Assumed is that it evaporates during the transit at sea or during the metallurgical processes. The environmental impacts of this are assumed to be low.</p>

### B.3. Input & Output Values DSM

	1+2 Paulikas et al.	3 Benchmark Minerals	4 Alvarange et al.	5 Fritz et al.
<b>Input Values</b>	<b>Collection of nodules:</b> Occupation seabed and ocean: 1.21E+02 m2 (0.0784 m2 for 0.648 kg dry nodules) Transformation of seabed: 1.21E+02 m2 (0.0784 m2 for 0.648 kg dry nodules) Diesel*: 5.09E+01 kWh (2.60E-03 kg for 0.648 kg dry nodules) <b>Offshore horizontal transport:</b> Distance exploitation to process site: 2.00E+03 km Transoceanic tanker*: 6.94E+01 kWh (1.88 tkm for 0.648 kg dry nodules) Heavy fuel oil*: 7.94E-04 kWh (1.85 J for 0.648 kg dry nodules) Electricity: 1.32E-04 kWh (8.57E-08 kWh for 0.648 kg dry nodules) <b>Total energy input collection + transportation:</b> 1.15E+02 kWh (8.57E-08 kWh + 1.85 J + 1.88 tkm + 2.6E-03 kg for 0.648 kg dry nodules)	<b>Collection of nodules:</b> Occupation seabed: 7.79E+01 m2 (738 km2a for 9.47 Mt dry nodules) Transformation of seabed: 1.66E+02 m2 (1570 km2 for 9.47 Mt dry nodules) Maine gas oil mining, survey and support vessels*: 2.61E+02 kWh (207.6 t for 9.47 Mt dry nodules) <b>Offshore horizontal transport:</b> Distance transshipment (port-to-port): 6.83E+03 km (3696 nautical miles) Gas oil transport vessels*: 8.82E+01 kWh (70.2 kt for 9.47 Mt dry nodules) Gas oil transshipment vessel (to Texas)*: 6.89E+01 kWh (54.3 kt for 9.47 Mt dry nodules) <b>Total energy input collection + transportation:</b> 4.18E+02 kWh (333 kt for 9.47 Mt dry nodules)	<b>Collection of nodules &amp; Offshore horizontal transport:</b> Heavy fuel (Scenario A): 4.69E+02 kWh Heavy fuel (Scenario B): 3.55E+02 kWh Distance exploitation to process site (Scenario A): 4.01E+03 km Distance exploitation to process site (Scenario B): 2.00E+03 km Distance by train: 1.00E+01 km Transportation by train*: 1.23E+00 kWh <b>Total energy input collection + transportation (Scenario A):</b> 4.70E+02 kWh <b>Total energy input collection + transportation (Scenario B):</b> 3.56E+02 kWh	<b>Collection of nodules:</b> Diesel for pumps*: 1.38E+01 kWh (33.5 Tj for 674 kt dry nodules) Diesel for marine engine*: 1.86E+02 kWh (5650 Mtkm for 674 kt dry nodules) <b>Offshore horizontal transport:</b> Distance exploitation to process site: 1.93E+03 km Diesel engine vessel*: 7.13E+01 kWh (2163 Mtkm for 674 kt dry nodules) <b>Total energy input collection + transportation:</b> 2.71E+02 kWh (33.5 Tj + 7813 Mtkm for 674 kt dry nodules)
	<b>Processing/Refining:</b> See Table 11 of Supplementary Data for conversion! Diesel (pyro): 1.60E-01 kt (1.04E-04 kg for 0.648 kg dry nodules) Natural gas (pyro): 5.39E+01 Nm3 (3.49E-02 Nm3 for 0.648 kg dry nodules) Sulfur (pyro): 5.49E+00 kg (3.96E-03 kg for 0.648 kg dry nodules) Silica sand (pyro): 8.79E+01 kg (5.70E-02 kg for 0.648 kg dry nodules) Electricity, hydropower (pyro+hydro): 4.97E+02 kWh (3.22E-04 MWh for 0.648 kg dry nodules) Compressed air (pyro): 2.68E-07 m3 (1.74E-10 m3 for 0.648 kg dry nodules) Hard coal (RM)/Mn Silicate slag: 1.53E+02 kg (9.90E-02 kg for 0.648 kg dry nodules) Oxygen, liquid (hydro): 7.61E+00 kg (4.93E-03 kg for 0.648 kg dry nodules) Sulfuric acid (hydro+Mn): 2.44E+03 kg (1.58 kg for 0.648 kg dry nodules) Sodium hydroxide (hydro): 1.11E-01 kg (7.16E-05 kg for 0.648 kg dry nodules) Ammonia, liquid (hydro+ Mn): 1.27E+02 kg (8.22E-02 kg for 0.648 kg dry nodules) Sulfur dioxide, liquid (hydro): 2.64E-02 kg (1.71E-05 kg for 0.648 kg dry nodules) Activated carbon (hydro): 6.96E-02 kg (4.51E-02 g for 0.648 kg dry nodules) Natural gas (hydro+Mn): 8.58E-02 Nm3 (5.56E-01 Nm3 for 0.648 kg dry nodules) Diesel (hydro): 1.92E-02 kg (1.24E-05 kg for 0.648 kg dry nodules) Lime (Mn): 5.02E+02 kg (3.26E-01 kg for 0.648 kg dry nodules) Hydrogen fluoride (Mn): 1.45E+02 kg (9.41E-02 kg for 0.648 kg dry nodules)	<b>Processing/Refining:</b> Bituminous coal (pyro) 9.71E+01 kt (474 kt for 4.88 Mt dry nodules) Natural gas (pyro) 3.81E+01 kg (186 kt for 4.88 Mt dry nodules) Sulphur (pyro) 6.35E+00 kg (31 kt for 4.88 Mt dry nodules) Silica flux (pyro): 8.34E+01 kg (407 kt for 4.88 Mt dry nodules) Electricity (pyro+hydro): 5.15E+02 kWh (2508.6 GWh for 4.88 Mt dry nodules) Heat (bituminous coal, pyro): 2.25E+03 MJ (11 PJ for 4.88 Mt dry nodules) Heat (natural gas, pyro): 2.05E+03 MJ (9.98 PJ for 4.88 Mt dry nodules) Water (pyro+hydro)*: 1.74E+03 m3 (5.8 hm3 + 2300 dam3 for 4.88 Mt dry nodules) Activated carbon, granular 9.05E-05 m3 Ammonia, liquid 9.92E+00 kg (48.4 kt for 4.88 Mt dry nodules) Oxygen, liquid 2.13E+01 kg (104 kt for 4.88 Mt dry nodules) Potassium hydroxide 3.30E-01 kg (1610 t for 4.88 Mt dry nodules) Sulphur acid 3.61E+01 kg (176 kt for 4.88 Mt dry nodules) Natural gas (hydro) 7.30E+00 kg (35.6 kt for 4.88 Mt dry nodules) Heat (natural gas, hydro): 3.87E+02 MJ (1890 Tj for 4.88 Mt dry nodules)	<b>Processing/Refining:</b> Electricity from renewables (Scenario A): 9.36E+02 kWh Electricity from renewables (Scenario B): 1.95E+02 kWh Thermal energy + electricity from Fossil & nuclear energy (Scenario A): 1.60E+03 kWh Thermal energy + electricity from Fossil & nuclear energy (Scenario B): 2.34E+03 kWh Reagents, SO2-process (sulfur, soda ash, dithydrogen sulfide): 1.48E+02 kg Reagents, HC FeMn smelting (metalurgical coke, graphite electrodes): 9.44E+01 kg Reagents, refining processes (lime, electrodes steel casting, alumina re): 1.86E+02 kg Water: 4.52E+03 kg Heavy fuel oil: 3.34E+01 kt (22.5 kt for 674 kt dry nodules) Hard coal: 3.25E+02 kg (219 kt for 674 kt dry nodules) Coke: 2.89E+03 MJ (1950 Tj for 674 kt dry nodules) Sulfuric acid: 3.69E+03 kg (24.9 kt for 674 kt dry nodules) Sodium sulfate: 3.26E-01 kg (0.22 kt for 674 kt dry nodules) Sodium chloride: 5.34E-02 kg (0.036 kt for 674 kt dry nodules) Silica sand: 2.80E+02 kg (189 kt for 674 kt dry nodules) Quicklime: 3.90E+01 kg (26.3 kt for 674 kt dry nodules) Polyacrylamide: 9.50E-02 kg (0.064 kt for 674 kt dry nodules) Oxygen, liquid: 9.72E+01 kg (65.5 kt for 674 kt dry nodules) Nitrogen: 4.99E+00 kg (3.36 kt for 674 kt dry nodules) Lime: 2.89E+01 kg (19.5 kt for 674 kt dry nodules) Hydrogen: 1.29E-01 kg (0.087 kt for 674 kt dry nodules) Hydrogen sulfide: 1.62E+00 kg (1.09 kt for 674 kt dry nodules) Gypsum: 1.18E+02 kg (79.4 kt for 674 kt dry nodules) Graphite: 1.41E+01 kg (9.53 kt for 674 kt dry nodules) Chlorine: 2.82E-02 kg (0.019 kt for 674 kt dry nodules) Carbon black: 5.34E-02 kg (0.036 kt for 674 kt dry nodules) Boric acid: 5.34E-02 kg (0.036 kt for 674 kt dry nodules) Ammonia: 1.28E+01 kg (8.63 kt for 674 kt dry nodules) Electricity: 8.34E+02 kWh (562 GWh for 674 kt dry nodules)	
<b>Output Values</b>	<b>Collection of nodules:</b> See Table 11 of Supplementary Data for conversion! CO2: 1.29E+01 kg (8.34E-03 kg for 0.648 kg dry nodules)	<b>Collection of nodules:</b> CO2: 6.71E+01 kg (524+40.2+71.6 kt for 9.47 Mt dry nodules) SOx: 6.96E-01 kg (5.04+0.334+0.85 kt for 9.47 Mt dry nodules) NOx: 2.54E-01 kg (2.01+0.134+0.26 kt for 9.47 Mt dry nodules) Wastewater: 1.05E-01 m3 (664+98+235 dam3 for 9.47 Mt dry nodules) Mobilised sediment: 1.81E+00 t (17.1 Mt for 9.47 Mt dry nodules)		
	<b>Offshore horizontal transport:</b> See Table 11 of Supplementary Data for conversion! Heat waste 3.17E+02 J (2.06E-07 MJ for 0.648 kg dry nodules) NMVOC 1.64E-01 g (1.07E-07 kg for 0.648 kg dry nodules)	<b>Offshore horizontal transport:</b> CO2: 4.16E+01 kg (221+173 kt for 9.47 Mt dry nodules) SOx: 4.47E-01 kg (2.2+2.03 kt for 9.47 Mt dry nodules) NOx: 1.90E-01 kg (0.99+0.812 kt for 9.47 Mt dry nodules) Wastewater: 6.92E-02 m3 (392+263 dam3 for 9.47 Mt dry nodules)		
	<b>Processing/Refining:</b> See Table 11 of Supplementary Data for conversion! CO2: 3.28E+02 kg (2.13E-01 kg for 0.648 kg dry nodules) CO: 8.73E-01 kg (5.69E-04 kg for 0.648 kg dry nodules) SOx: 2.60E+00 kg (1.69E-03 kg for 0.648 kg dry nodules) Ammonia sulphate: 3.50E+01 kg (2.27E-02 kg for 0.648 kg dry nodules) Ni sulfate: 1.25E+01 kg (8.10E-03 kg for 0.648 kg dry nodules) Cu: 1.00E+01 kg (6.50E-03 kg for 0.648 kg dry nodules) Co sulfate: 1.23E+00 kg (8.00E-04 kg for 0.648 kg dry nodules) Mn: 2.84E+02 kg (1.84E-01 kg for 0.648 kg dry nodules)	<b>Processing/Refining:</b> Steam (pyro) 1.06E+03 t (5.18 Gt for 4.88 Mt dry nodules) Slag mass 7.66E-01 t (3.74 Mt for 4.88 Mt dry nodules) Steam (hydro) 5.80E-01 m3 (2830 dam3 for 4.88 Mt dry nodules) Wastewater: 1.20E-02 m3 (58.7 dam3 for 4.88 Mt dry nodules) Ammonium sulphate: 3.93E+01 kg (192 kt for 4.88 Mt dry nodules) Ni: 1.32E+01 kg (64.2 kt for 4.88 Mt dry nodules) Cu: 9.84E+00 kg (48 kt for 4.88 Mt dry nodules) Co: 1.08E+00 kg (5.27 kt for 4.88 Mt dry nodules)	<b>Processing/Refining:</b> CO2 1.38E+02 kg CO 8.80E+01 kg Residues, SO2-process (tailings, neutralization residues, bleed) 1.24E+03 kg Residues, refining processes (slag, gypsum): 3.17E+02 kg Water, to air: 1.45E+02 kg Wastewater: 3.82E+03 kg Ni: 1.28E+01 kg Cu: 1.05E+01 kg Co: 2.30E+00 kg Fe: 3.11E+02 kg CO2: 1.11E+03 kg (745 kt for 674 kt dry nodules) Gypsum: 2.37E+02 kg (16 kt for 674 kt dry nodules) Inert waste: 6.62E+02 kg (446 kt for 674 kt dry nodules) Nickel smelter slag: 8.03E+02 kg (541 kt for 674 kt dry nodules) Cathode-Ni: 1.93E+01 kg (10.3 kt for 674 kt dry nodules) Co-powder: 2.15E+00 kg (1.45 kt for 674 kt dry nodules) Cathode-Cu: 1.17E+01 kg (7.89 kt for 674 kt dry nodules) FeMn: 3.38E+02 kg (228 kt for 476 kt dry nodules)	
	* Energy consumption diesel: 12.6 kWh/kg Energy consumption marine gas oils 11.9 kWh/kg 1 Tj = 277777.778 kWh Water density: 1000 kg/m3 Energy consumption rail: 0.31 MJ/km Energy consumption ocean freight: 0.08 MJ/km	(https://www.cevalogistics.com/en/glossary/watt-hours-kilogram) (https://www.joostdevree.nu/shtmls/calorische_waarde.shtml) (https://www.convertunits.com/from/Tj/to/kilowatt+hours) (https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html) (https://bit.deutschebahn.com/2023/en/combined-management-report/green-transformation/climate-protection/energy-efficiency/) (https://bit.deutschebahn.com/2023/en/combined-management-report/green-transformation/climate-protection/energy-efficiency/)		

### **Energy Input Excavation & Transport**

*Paulikas et al. (2020b, 2020a)*: Energy use for collection and transport is  $8.57E-08 \text{ kWh} + 1.85 \text{ J} + 1.88 \text{ tkm} + 2.6E-03 \text{ kg}$  for 0.648 kg dry nodules = 115 kWh for 1 tonne dry nodules, assuming energy consumption of ocean freight of 0.022 kWh/tkm (DB, 2023) and of diesel of 12.6 kWh/kg (CEVA Logistics, 2025).

*Benchmark Mineral Intelligence (2022)*: Energy use for collection and transport is 333 kt for 9.47 Mt dry nodules = 418 kWh for 1 tonne dry nodules, with energy consumption of marine gas oils of 11.9 kWh/kg (De Vree, n.d.).

*Alvarenga et al. (2022)*:

Scenario A: Energy use rail is 0.31 MJ/tkm (DB, 2023). This equals 0.086 kWh/tkm. So, energy for rail is  $(0.086 \times 14.3) = 1.23 \text{ kWh}$ . Energy for collection and offshore horizontal transport is 469 kWh.

Scenario B: Energy use rail is 1.23 kWh (see above) and 355 kWh for the collection and offshore horizontal transport.

*Fritz et al. (2023)*: Energy use collection and transport is 33.5 TJ + 7813 Mtkm for 674 kt dry nodules = 271 kWh for 1 tonne of dry nodules, with energy use ocean freight of 0.022 kWh/tkm (DB, 2023).

### **Electricity Input Processing & Refining**

*Paulikas et al. (2020b, 2020a)*:  $3.05E-04 + 1.68E-05 \text{ MWh}$  for 0.648 kg dry nodules = 497 kWh for 1 tonne of dry nodules.

*Benchmark Mineral Intelligence (2022)*:  $2230 + 9.37 + 266 + 3.2$  for 4.88 Mt dry nodules = 515 kWh for 1 tonne dry nodules.

*Alvarenga et al. (2022)*:

Scenario A:  $936 \text{ kWh} + 1603 \text{ kWh} = 2539 \text{ kWh}$ .

Scenario B:  $195 \text{ kWh} + 2344 \text{ kWh} = 2539 \text{ kWh}$ .

*Fritz et al. (2023)*: 562 GWh for 674 kt dry nodules = 834 kWh for 1 tonne of dry nodules.

### **Water Input Processing & Refining**

*Benchmark Mineral Intelligence (2022)*:  $5.18 \text{ hm}^3 + 3300 \text{ dam}^3$  for 4.88 Mt dry nodules =  $1738 \text{ m}^3$  for 1 tonne dry nodules, with water density  $1000 \text{ kg/m}^3$ .

*Fritz et al. (2023)*: 2.66 Mt for 674 kt dry nodules =  $3947 \text{ m}^3$  for 1 tonne of dry nodules.

### **Silicia Sand/Flux Input Processing & Refining**

*Paulikas et al. (2020b, 2020a)*: 570 kg for 0.648 kg dry nodules = 88 kg for 1 tonne dry nodules.

*Benchmark Mineral Intelligence (2022)*: 407 kt for 4.88 Mt dry nodules = 83 kg for 1 tonne dry nodules.

*Fritz et al. (2023)*: 189 kt for 674 kt dry nodules = 280 kg for 1 tonne dry nodules.

### **CO<sub>2</sub> Emissions Processing & Refining**

*Paulikas et al. (2020b, 2020a)*: 0.2127 kg for 0.648 kg dry nodules = 328 kg for 1 tonne dry nodules.

*Fritz et al. (2023)*: 745 kt for 674 kt dry nodules = 1105 kg for 1 tonne of dry nodules.

## B.4. Life-Cycle Impact Assessment

	1	2	3	4	5
	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Paulikas, Katona, Ilves, and Ali	Benchmark Mineral Intelligence	Alvarange et al.	Fritz et al.
# included impact categories	16 (+ 2 economic impact categories + not quantified biodiversity loss risk)	2	21	3	1
Included impact categories	Climate change: GWP Climate change: Stored carbon Ore use Land use Seabed use Water use Energy resources Solid waste Ecotoxicity terrestrial Ecotoxicity freshwater Eutrophication Human toxicity Human lives at risk Megafauna wildlife at risk Biomass at risk SOx and NOx emissions (Life cycle inventory) Biodiversity loss risk (not quantified) Nickel sulfate production cost (economic impact) Jobs created (economic impact)	Climate change: GWP Climate change: Stored carbon	Climate change: GWP Ozone depletion Particulate matter formation Terrestrial acidification Freshwater eutrophication Marine eutrophication Water use Ionising radiation Ozone formation: human health Ozone formation: terrestrial ecosystems Ecotoxicity terrestrial Ecotoxicity freshwater Ecotoxicity marine Human toxicity carcinogenic Human toxicity non-carcinogenic Land use Mineral resource scarcity Energy resource scarcity Human health (endpoint) Ecosystems (endpoint) Resources (endpoint)	Climate change: GWP Photochemical oxidant formation Acidification	Climate change: GWP
Characterization method	<b>Climate change (GWP)</b> : GWP100 <b>Stored carbon</b> : Modeled per area / Calculated <b>Land use</b> : CML indicator <b>Seabed use</b> : Comparables / Modeled / Calculated <b>Water use</b> : Comparables <b>Energy resources</b> : CED indicator <b>Solid waste</b> : Comparables/Modelled/Literature review <b>Ecotoxicity terrestrial</b> : CML indicator <b>Ecotoxicity freshwater</b> : CML indicator <b>Eutrophication</b> : CML indicator <b>Human toxicity</b> : CML indicator <b>Megafauna wildlife at risk</b> : Literature review <b>Biomass at risk</b> : Literature review	<b>Climate change</b> : GWP100	Characterization factors from ReCipe2016.	<b>Climate change</b> : GWP100 Characterization factor from IPCC (2013)  <b>Photochemical oxidant formation</b> : LOTOS-EUROS Characterization factor from ReCiPe2008.  <b>Acidification</b> : Accumulated Exceedance	<b>Climate change</b> : GWP100 Characterization factor from IPCC (2013).
Normalization?	NO	NO	NO	NO	NO

## B.5. Characterization Results

<b>Climate change (GWP)</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt CO2-eq	1,85E+03	4,45E+02	-75,9%	For 1 billion EVs	Baseline land-ores scenario
			1,47E+03	4,45E+02	-69,7%	For 1 billion EVs	Green land-ores scenario
2	Paulikas, Katona, Ilves, and Ali	Mt CO2-eq	1,85E+03	4,45E+02	-75,9%	For 1 billion EVs	Baseline land-ores scenario
			1,47E+03	4,45E+02	-69,7%	For 1 billion EVs	Green land-ores scenario
3	Benchmark Minerals	kg CO2-eq	1,26E+01	4,91E+00	-61,2%	For 1 kg Ni/Cu/Co matte	
		kg CO2-eq	2,85E+01	6,17E+00	-78,3%	For 1 kg Ni in Nickel sulphate	
		kg CO2-eq	6,27E+01	1,64E+01	-73,8%	For 1 kg Co in Cobalt sulphate	
		kg CO2-eq	1,21E+01	2,84E+00	-76,5%	For 1 kg Cu cathode	
4	Alvarange et al.	kg CO2-eq	2,19E+03	1,37E+03	-37,5%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	Scenario A
		kg CO2-eq	2,19E+03	1,83E+03	-16,5%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	Scenario B
5	Fritz et al.	kg CO2-eq	2,78E+00	2,03E+00	-27,0%	For 15.3 g Ni, 11.7 g Cu, 2.2 g Co, and 338 g FeMn.	
<b>Climate change (stored carbon)</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Gt CO2	9,30E+00	6,00E-01	-93,5%	For 1 billion EVs	
2	Paulikas, Katona, Ilves, and Ali	metric Mt CO2	9,30E+03	5,83E+02	-93,7%	For 1 billion EVs	Stored carbon at risk
		metric Mt CO2	2,06E+03	2,44E+02	-88,2%	For 1 billion EVs	Disrupted carbon stored over 100 years
<b>Acidification</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg SO2-eq	5,07E-02	3,27E-02	-35,5%	For 1 kg Ni/Cu/Co matte	Terrestrial acidification
		kg SO2-eq	1,32E-01	3,09E-02	-76,5%	For 1 kg Ni in Nickel sulphate	Terrestrial acidification
		kg SO2-eq	2,72E-01	8,22E-02	-69,8%	For 1 kg Co in Cobalt sulphate	Terrestrial acidification
		kg SO2-eq	5,12E-02	1,42E-02	-72,2%	For 1 kg Cu cathode	Terrestrial acidification
4	Alvarange et al.	mol H <sup>+</sup> -eq	4,20E+01	1,15E+01	-72,6%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	Terrestrial + Freshwater acidification
		mol H <sup>+</sup> -eq	4,20E+01	1,27E+01	-69,8%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	Terrestrial + Freshwater acidification
<b>Ecotoxicity freshwater</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Gt 1,4-DCB-eq	2,10E+01	1,00E-01	-99,5%	For 1 billion EVs	
3	Benchmark Minerals	kg 1,4-DCB-eq	2,64E+01	5,48E-02	-99,8%	For 1 kg Ni/Cu/Co matte	
		kg 1,4-DCB-eq	3,91E+01	-1,78E-01	-100,5%	For 1 kg Ni in Nickel sulphate	
		kg 1,4-DCB-eq	1,02E+02	-4,74E-01	-100,5%	For 1 kg Co in Cobalt sulphate	
		kg 1,4-DCB-eq	1,75E+01	-8,19E-02	-100,5%	For 1 kg Cu cathode	
<b>Ecotoxicity marine</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg 1,4-DCB-eq	3,28E+01	7,51E-02	-99,8%	For 1 kg Ni/Cu/Co matte	
		kg 1,4-DCB-eq	4,85E+01	-1,75E-01	-100,4%	For 1 kg Ni in Nickel sulphate	
		kg 1,4-DCB-eq	1,26E+02	-4,66E-01	-100,4%	For 1 kg Co in Cobalt sulphate	
		kg 1,4-DCB-eq	2,18E+01	-8,05E-02	-100,4%	For 1 kg Cu cathode	

<b>Ecotoxicity terrestrial</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt 1,4-DCB-eq	3,30E+01	5,00E-01	-98,5%	For 1 billion EVs	
3	Benchmark Minerals	kg 1,4-DCB-eq	5,28E+00	2,95E+00	-44,1%	For 1 kg Ni/Cu/Co matte	
		kg 1,4-DCB-eq	5,92E+01	-1,29E+01	-121,8%	For 1 kg Ni in Nickel sulphate	
		kg 1,4-DCB-eq	3,34E+01	-3,43E+01	-203,0%	For 1 kg Co in Cobalt sulphate	
		kg 1,4-DCB-eq	5,87E+00	-5,94E+00	-201,2%	For 1 kg Cu cathode	
<b>Energy resource scarcity</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	PJ	2,62E+04	2,53E+04	-3,4%	For 1 billion EVs	Baseline land-ores scenario
		PJ	2,45E+04	2,53E+04	3,3%	For 1 billion EVs	Green land-ores scenario
3	Benchmark Minerals	kg oil-eq	3,00E+00	1,03E+00	-65,8%	For 1 kg Ni/Cu/Co matte	
		kg oil-eq	6,44E+00	1,34E+00	-79,2%	For 1 kg Ni in Nickel sulphate	
		kg oil-eq	1,39E+01	3,56E+00	-74,4%	For 1 kg Co in Cobalt sulphate	
		kg oil-eq	2,72E+00	6,16E-01	-77,3%	For 1 kg Cu cathode	
<b>Eutrophication freshwater</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt PO4-eq	8,00E+01	6,00E-01	-99,3%	For 1 billion EVs	Not specified if it is freshwater or marine eutrophication
3	Benchmark Minerals	kg P-eq	4,65E-02	1,36E-03	-97,1%	For 1 kg Ni/Cu/Co matte	
		kg P-eq	7,64E-02	9,84E-04	-98,7%	For 1 kg Ni in Nickel sulphate	
		kg P-eq	1,83E-01	2,62E-03	-98,6%	For 1 kg Co in Cobalt sulphate	
		kg P-eq	3,43E-02	4,53E-04	-98,7%	For 1 kg Cu cathode	
<b>Eutrophication marine</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt PO4-eq	8,00E+01	6,00E-01	-99,3%	For 1 billion EVs	Not specified if it is freshwater or marine
3	Benchmark Minerals	kg N-eq	1,23E-03	8,22E-05	-93,3%	For 1 kg Ni/Cu/Co matte	
		kg N-eq	2,30E-03	-2,15E-03	-193,4%	For 1 kg Ni in Nickel sulphate	
		kg N-eq	5,04E-03	-5,71E-03	-213,4%	For 1 kg Co in Cobalt sulphate	
		kg N-eq	1,03E-03	-9,87E-04	-196,0%	For 1 kg Cu cathode	
<b>Human toxicity carcinogenic</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt 1,4-DCB-eq	3,70E+04	2,86E+02	-99,2%	For 1 billion EVs	Not specified if it is carcinogenic or non-
3	Benchmark Minerals	kg 1,4-DCB	1,64E+00	1,32E-01	-92,0%	For 1 kg Ni/Cu/Co matte	
		kg 1,4-DCB	2,97E+00	-2,73E-03	-100,1%	For 1 kg Ni in Nickel sulphate	
		kg 1,4-DCB	6,69E+00	-7,26E-03	-100,1%	For 1 kg Co in Cobalt sulphate	
		kg 1,4-DCB	1,29E+00	-1,25E-03	-100,1%	For 1 kg Cu cathode	

<b>Human toxicity non-carcinogenic</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt 1,4-DCB-eq	3,70E+04	2,86E+02	-99,2%	For 1 billion EVs	Not specified if it is carcinogenic or non-
3	Benchmark Minerals	kg 1,4-DCB	2,56E+02	1,92E+00	-99,3%	For 1 kg Ni/Cu/Co matte	
		kg 1,4-DCB	3,89E+02	-9,79E-01	-100,3%	For 1 kg Ni in Nickel sulphate	
		kg 1,4-DCB	9,90E+02	-2,61E+00	-100,3%	For 1 kg Co in Cobalt sulphate	
		kg 1,4-DCB	1,73E+02	-4,50E-01	-100,3%	For 1 kg Cu cathode	
<b>Ionising radiation</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kBq Co-60-eq	1,33E-01	1,10E-02	-91,8%	For 1 kg Ni/Cu/Co matte	
		kBq Co-60-eq	2,48E-01	-4,68E-02	-118,9%	For 1 kg Ni in Nickel sulphate	
		kBq Co-60-eq	3,70E+00	-1,25E-01	-103,4%	For 1 kg Co in Cobalt sulphate	
		kBq Co-60-eq	9,54E-02	-2,15E-02	-122,6%	For 1 kg Cu cathode	
<b>Land use</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	km2	1,56E+05	9,80E+03	-93,7%	For 1 billion EVs	
3	Benchmark Minerals	m2a crop-eq	4,45E+01	5,76E-02	-99,9%	For 1 kg Ni/Cu/Co matte	
		m2a crop-eq	6,49E+01	2,91E-02	-100,0%	For 1 kg Ni in Nickel sulphate	
		m2a crop-eq	1,72E+02	7,75E-02	-100,0%	For 1 kg Co in Cobalt sulphate	
		m2a crop-eq	2,94E+01	1,34E-02	-100,0%	For 1 kg Cu cathode	
<b>Mineral resource scarcity</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg Cu-eq	2,77E+00	2,52E-01	-90,9%	For 1 kg Ni/Cu/Co matte	
		kg Cu-eq	4,06E+00	2,79E-01	-93,1%	For 1 kg Ni in Nickel sulphate	
		kg Cu-eq	1,07E+01	7,42E-01	-93,0%	For 1 kg Co in Cobalt sulphate	
		kg Cu-eq	1,83E+00	1,28E-01	-93,0%	For 1 kg Cu cathode	
<b>Ozone depletion</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg CFC11-eq	1,59E-05	7,36E-07	-95,4%	For 1 kg Ni/Cu/Co matte	
		kg CFC11-eq	2,71E-05	7,33E-07	-97,3%	For 1 kg Ni in Nickel sulphate	
		kg CFC11-eq	6,44E-05	1,95E-06	-97,0%	For 1 kg Co in Cobalt sulphate	
		kg CFC11-eq	1,20E-05	3,37E-07	-97,2%	For 1 kg Cu cathode	
<b>Ozone formation: Human health</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg NOx-eq	8,77E-02	1,21E-02	-86,2%	For 1 kg Ni/Cu/Co matte	
		kg NOx-eq	1,46E-01	1,28E-02	-91,2%	For 1 kg Ni in Nickel sulphate	
		kg NOx-eq	3,51E-01	3,40E-02	-90,3%	For 1 kg Co in Cobalt sulphate	
		kg NOx-eq	6,28E-02	5,88E-03	-90,6%	For 1 kg Cu cathode	

<b>Ozone formation: Terrestrial ecosystems</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg NOx-eq	8,91E-02	1,22E-02	-86,3%	For 1 kg Ni/Cu/Co matte	
		kg NOx-eq	1,48E-01	1,28E-02	-91,4%	For 1 kg Ni in Nickel sulphate	
		kg NOx-eq	3,56E-01	3,40E-02	-90,4%	For 1 kg Co in Cobalt sulphate	
		kg NOx-eq	6,37E-02	5,88E-03	-90,8%	For 1 kg Cu cathode	
<b>Particulate matter formation</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	kg PM2.5-eq	1,70E-02	9,79E-03	-42,4%	For 1 kg Ni/Cu/Co matte	
		kg PM2.5-eq	4,29E-02	9,23E-03	-78,5%	For 1 kg Ni in Nickel sulphate	
		kg PM2.5-eq	8,89E-02	2,46E-02	-72,4%	For 1 kg Co in Cobalt sulphate	
		kg PM2.5-eq	1,66E-02	4,24E-03	-74,4%	For 1 kg Cu cathode	
<b>Photochemical oxidant formation</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
4	Alvarange et al.	kg NMVOC-eq	8,90E+00	8,70E+00	-2,2%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	(Scenario A)
		kg NMVOC-eq	8,90E+00	9,50E+00	6,7%	For 12.8 kg Ni, 10.5 kg Cu, 2.3 kg Co, 311.3 kg FeMn.	(Scenario B)
<b>Water use</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	km3	4,50E+01	5,00E+00	-88,9%	For 1 billion EVs	
3	Benchmark Minerals	m3	4,05E-02	3,68E-03	-90,9%	For 1 kg Ni/Cu/Co matte	
		m3	1,25E-01	5,46E-02	-56,5%	For 1 kg Ni in Nickel sulphate	
		m3	3,16E-01	1,45E-01	-54,0%	For 1 kg Co in Cobalt sulphate	
		m3	4,43E-02	2,51E-02	-43,4%	For 1 kg Cu cathode	
<b>Human health (endpoint)</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	DALY	8,63E-05	1,16E-05	-86,6%	For 1 kg Ni/Cu/Co matte	
		DALY	1,52E-04	1,14E-05	-92,5%	For 1 kg Ni in Nickel sulphate	
		DALY	3,63E-04	3,04E-05	-91,6%	For 1 kg Co in Cobalt sulphate	
		DALY	6,55E-05	5,25E-06	-92,0%	For 1 kg Cu cathode	
<b>Human lives at risk</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	number	1,80E+03	4,70E+01	-97,4%	For 1 billion EVs	

<b>Ecosystems (endpoint)</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	species.yr	5,05E-07	2,38E-08	-95,3%	For 1 kg Ni/Cu/Co matte	
		species.yr	7,88E-07	2,69E-08	-96,6%	For 1 kg Ni in Nickel sulphate	
		species.yr	2,01E-06	7,15E-08	-96,4%	For 1 kg Co in Cobalt sulphate	
		species.yr	3,51E-07	1,24E-08	-96,5%	For 1 kg Cu cathode	
<b>Resources (endpoint)</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
3	Benchmark Minerals	USD2013	1,07E+00	2,50E-01	-76,6%	For 1 kg Ni/Cu/Co matte	
		USD2013	1,84E+00	3,70E-01	-79,9%	For 1 kg Ni in Nickel sulphate	
		USD2013	4,45E+00	9,70E-01	-78,2%	For 1 kg Co in Cobalt sulphate	
		USD2013	7,80E-01	1,70E-01	-78,2%	For 1 kg Cu cathode	
<b>Solid waste</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Gt	6,40E+01	0,00E+00	-100,0%	For 1 billion EVs	
<b>Ore use</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Gt	2,50E+01	6,00E+00	-76,0%	For 1 billion EVs	
<b>Seabed use</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	km2	2,00E+03	5,08E+05	25300,0%	For 1 billion EVs	
<b>Megafauna wildlife at risk</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	trillion organisms	4,70E+01	3,00E+00	-93,6%	For 1 billion EVs	
<b>Biomass at risk</b>							
No.	Authors	Unit	Land-based ores	Nodules	% Difference*	Reference flow	Comment
1	Paulikas, Katona, Ilves, Stone, and O'Sullivan	Mt	5,68E+02	4,20E+01	-92,6%	For 1 billion EVs	

\* Percentage difference of deep-sea alternative relative to the land alternative.

## B.6. Results & Recommendations

	1	2	3	4	5
	Paulikas, Katona, Ives, Stone, and O'Sullivan	Paulikas, Katona, Ives, and Ali	Benchmark Minerals	Alvarange et al.	Fritz et al.
<b>Contribution analysis DSM alternative</b>	<p>- Pyrometallurgical processing is contributing most to the climate change impact of metals from nodules, because the reduction of oxides in the nodules is coal-intensive.</p> <p>- Less than 10% is caused by the offshore collection and transport.</p> <p>- Refining process has lower contribution because of the use of hydropower.</p>	<p>- Pyrometallurgical processing is contributing most to the climate change impact of metals from nodules, because the reduction of oxides in the nodules is coal-intensive.</p> <p>- Less than 10% is caused by the offshore collection and transport.</p> <p>- Refining process has lower contribution because of the use of hydropower.</p>	<p>- The production, distribution, and combustion of bituminous coal have the largest contribution to most impact categories.</p> <p>- The pyrometallurgical process has the largest climate change impact. Combustion of bituminous coal contributes to 63-65% of the climate change impacts.</p>	<p>- Onshore processes (e.g. metallurgical processing) are the main contributors to the total environmental impacts, for all 3 impact categories.</p> <p>- These are significantly influenced by the energy sources.</p> <p>- Offshore processes have a minor influence on the total environmental impacts, especially for photochemical oxidant formation and climate change.</p> <p>- Shipment to onshore can significant contribute to the total environmental impacts, depended on the location of the onshore site (especially for acidification).</p>	<p>- Metallurgy processing contributes most to the climate change impacts (95%).</p> <p>- The reduction process of FeMn, using coal, accounts for 55% of the total climate change impact, because it emits high amounts of greenhouse gasses.</p> <p>- Electricity consumption during refining accounts for 1/4 of the total climate change impacts, because the Mexican electricity grid has a high share of fossil energy.</p> <p>- The supply of oxygen causes about 5% of the total emissions from metal production.</p> <p>- FeMn is the metal that contributes most to the climate change impacts of both alternatives.</p>
<b>Contribution analysis land-mining alternative</b>	<p>Mining and concentration processes contribute to about half of the climate change impacts. These processes are energy- and material-intensive.</p>	<p>Mining and concentration processes contribute to about half of the climate change impacts. These processes are energy- and material-intensive.</p>	<p>- Electricity use from Australia's carbon intense energy mix is the main contributor to the climate change impacts.</p> <p>- The production of sulphidic tailings is the main contributor to human health impacts and freshwater eutrophication emissions.</p> <p>- Blasting is the main contributor to particulate matter formation, ozone depletion, and terrestrial acidification.</p>	<p>- Energy use is the main contributor to the impacts for Ni, Co, Cu, and FeMn production.</p> <p>- FeMn is the metal that is the main contributor to the total impacts on climate change and photochemical oxidant formation, in absolute terms.</p> <p>- Ni is the metal that is the main contributor to the total impact on acidification, in absolute terms.</p> <p>- Co is the metal that is the main relative contributor to the impact on climate change.</p> <p>- Ni is the metal that is the main relative contributor to the impact on acidification.</p> <p>- Co &amp; Ni are the main relative contributors to the impact on photochemical oxidant formation.</p>	<p><b>Kevitsa (Ni):</b> Metallurgical processing has a relatively low contribution to climate change impacts, because of the high amount of hydropower in the electricity mix in Finland. Diesel fuel for mining contributes 45% to the climate change impacts. Electricity use contributes 27% to the impacts.</p> <p><b>Murrin Murrin (Ni/Co):</b> Natural gas and electricity that is used contributes 65% to the climate change impacts. Besides, the supply chains of sulfur and lime indirectly contributes to 15% of the climate change impacts. Diesel combustion in mining contributes 10% to the impacts and electricity for crushing contributes 6%.</p> <p><b>Woodie Woodie (FeMn):</b> Pyrometallurgical processing is the main contributor to the climate change impacts. The use of Chinese electricity (mostly fossil fuels) and the use of coal/coke for the reduction of oxides contributes to more than 75% of the climate change impacts.</p> <p>FeMn is the metal that contributes most to the climate change impacts of both alternatives.</p>
<b>Sensitivity analysis</b>	<p><b>Allocation method:</b> Physical allocation instead of economic allocation results in significant reduction of emissions for both alternatives, but especially for the deep-sea nodules alternative. This is because the ammonium sulfate of the DSM alternative receives a much larger allocation, which reduced the emissions of the metals. The lower climate change impacts of the nodules compared to the land-based ores is robust for both allocation methods, but the nodules alternative becomes even more beneficial in terms of climate change impacts when using physical allocation.</p>	<p><b>Allocation method:</b> Physical allocation instead of economic allocation results in significant reduction of emissions for both alternatives, but especially for the deep-sea nodules alternative. This is because the ammonium sulfate of the DSM alternative receives a much larger allocation, which reduced the emissions of the metals. The lower climate change impacts of the nodules compared to the land-based ores is robust for both allocation methods, but the nodules alternative becomes even more beneficial in terms of climate change impacts when using physical allocation.</p>	<p><b>Allocation method:</b> Economic allocation for the pyrometallurgical process instead of physical allocation. All impact categories are significantly impacted by this change, especially the impact on water consumption.</p> <p><b>Location onshore processing DSM:</b> 1: Texas (baseline): 100% wind energy, 3684 nautical miles port-to-port 2: India: Solar energy with ESS, 9500 nautical miles port-to-port 3: Malaysia: 100% hydro power, 7300 nautical miles port-to-port The location of onshore processing of the nodules does not significantly impact the climate change results. This is because transshipment vessels for the transportation to the onshore site have a low contribution to the climate change impacts.</p> <p><b>Metal price variation:</b> Average of 10 year, versus prices of 2022. Metal price variation still result in the same patterns, however noticeable is that while absolute prices change, hierarchy between the impacts of co-products will not.</p> <p><b>Environmental credit:</b> Ammonium sulphate via system expansion, versus co-production with economic allocation of 1%. All impact categories are significantly impacted by this change, especially the impact on marine eutrophication is much higher with economic allocation.</p> <p>So, the results are sensitive to environmental credits and economic allocation, but not to metal prices and the onshore production location.</p>	n/a	<p><b>Allocation method:</b> Economic allocation, except for the FeMn reduction process, instead of economic allocation in the entire system. This results in a significant higher contribution of FeMn to the total climate change impacts, but the total climate change impacts stay similar.</p> <p><b>Market price:</b> High market prices for ZnS and CuS (3 euro/kg) results in a decrease of the climate change impacts of less than 1%.</p> <p><b>Electricity mix for processing nodules:</b> Norwegian electricity mix (lowest CO2-eq in Ecoinvent) instead of the Mexican electricity mix. This reduces the total climate change impacts of the nodules with about 20%.</p> <p><b>Electricity mix for land-based ores:</b> Norwegian electricity mix (lowest CO2-eq in Ecoinvent). This decreases the climate change impacts of Kevitsa by 25% and of Woodie Woodie by 50%.</p>

<p><b>Conclusions</b></p>	<ul style="list-style-type: none"> <li>- Metals production from polymetallic nodules potentially have significant advantages over land-based ores across almost all impact categories.</li> <li>- <b>Climate change</b> impacts would be significantly lower if metals are produced from polymetallic nodules. This is because of the lower energy requirements, lower transport costs, and easy accessibility of hydropower (or other renewables). The flexibility of placing metallurgical plants near a port allows access to hydropower, other renewables and byproducts and markets. While land-based mining requires metallurgical plants close to the mines, because of their high mass.</li> <li>- Impacts on <b>nonliving resource</b>, such as the usage and pollution of land, water, forest, and soil, would be significantly lower if metals are produced from polymetallic nodules.</li> <li>- The impact on <b>seafloor use</b> would be much higher for polymetallic nodules. The main advantage of land-based mining in comparison to DSM is the avoidance of disturbing a large area of which we have insufficient knowledge.</li> </ul>	<p>The climate change impacts are substantially lower for metals from polymetallic nodules compared to land-based ores. This is because the collection of the nodules is low-energy-intensive, they have high ore grades, and the ocean location enables ship transport to the onshore plant with low emissions.</p> <p>The flexibility of placing metallurgical plants near a port allows access to hydropower, other renewables and byproducts and markets. While land-mining requires metallurgical plants close to the mines, because of their high mass.</p>	<ul style="list-style-type: none"> <li>- DSM has better environmental performance than traditional land-mining in the majority of the impact categories.</li> <li>- Lower emissions of DSM compared to land-mining may be due to the absence of blasting and sulphidic tailings in DSM processes.</li> <li>- Lower impact of DSM compared to land-mining may be due to the availability of renewable electricity in Texas, high-volume and high-revenue co-products, and a high metal recovery rate.</li> <li>- The deep-sea nodules alternative has lower electricity demand, higher value and volume co-products, no blasting during mining and no production of sulphidic tailings during processing, renewable electricity use, oxygen production with renewable electricity on site, and high metal recovery rates.</li> <li>- The higher ore grades of polymetallic nodules results in less energy use.</li> <li>- For the land-based mining alternative, electricity use is one of the top hotspots for all impact categories. The use of renewables in the nodules alternative plays an important role in outperforming the land-mining alternative.</li> </ul>	<ul style="list-style-type: none"> <li>- Scenario A has less environmental impacts than Scenario B, in order of 8-25%.</li> <li>- Metals from DSM potentially result in less impact on climate change than land-based ores (in order of 16-38%).</li> <li>- Metals from DSM potentially result in similar impacts on photochemical oxidant formation as land-based ores.</li> <li>- Metals from DSM potentially result in less impact on acidification than land-based ores (in order of 70-73%).</li> <li>- Metals from deep-sea mining can bring environmental gains to society as alternative source of metals for 3 impact categories.</li> <li>- Clean energy supply for onshore processing is important for the environmental performance. For example, by locating the processing plant at a region with renewables in the electricity grid, or by directly purchasing renewable energy.</li> <li>- DSM has the advantage that you can choose the location of the onshore processes. This is important for the environmental performances and sustainability performances in general.</li> </ul>	<p>The climate change impact (GWP) of metals from polymetallic nodules compared to the current land-mining is approximately 27% lower. Compared to literature from the industry this impact is about 16% lower. Compared to Ecoinvent v3.7.1, this impact is about 28% higher.</p> <p>The study shows that producing metals from polymetallic nodules can lead to lower or higher climate change impacts in comparison with land-mining, depending on the methodological choices and model input.</p>
<p><b>Recommendations</b></p>	<p>Further assessment of the environmental impact of nodule collection on ecosystem function and seabed life is required.</p>	<ul style="list-style-type: none"> <li>- Further research should consider sustainability impacts more broadly, such as social impacts.</li> <li>- Further research should examine if new metal supply could indirectly impact metal consumption, investments in recycling developments, and have policy externalities.</li> <li>- Further research should model additional metallurgical pathways, as this is a main contributor to the climate change impacts.</li> <li>- The land-based alternative should be updated if new pathways become available.</li> <li>- The land-mining and deep-sea mining industries should assemble representative databases.</li> <li>- Purchasers of metals should consider the land-based ores versus nodules results by setting up a supply-chain.</li> </ul>	<ul style="list-style-type: none"> <li>- Find a replacement for metallurgical coal as reductant to reduce total emissions of DSM.</li> <li>- Ammonia and sulphuric acid need to be sourced from suppliers that produce fewer emissions or they should be designed more efficiently.</li> <li>- Sediment composition should be assessed in future research.</li> <li>- Further research should take a "basket of products" approach.</li> <li>- Further research should include new scenarios based on new studies.</li> <li>- The LCIA method should be improved to account for the transformation and occupation of seabed in the ecosystem analysis.</li> </ul>	<ul style="list-style-type: none"> <li>- Further study should assess the impact of metallurgical processing of nodules by using a metallurgical process simulation, to get more insights on different smelting and refining processes and their hotspots.</li> <li>- Further studies with different scenarios could tackle the issue of many assumptions and uncertainties.</li> <li>- Further research should combine the results with market forecasts.</li> </ul>	<p>Decision-making about polymetallic nodule exploitation should not only be based on climate change.</p>

# Appendix C: Unit-Process Tables

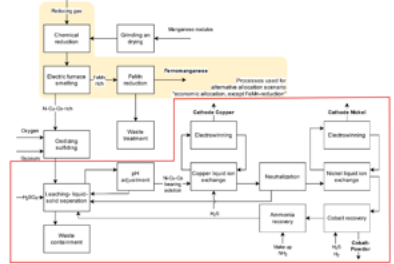
## C.1. Unit-Process Table DSM

Unit Process: Collection & Vertical Transport (P1)							
Economic flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
21,91	kg	light fuel oil	market for light fuel oil   light fuel oil   Cutoff, U-RoW	P6	RoW	Benchmark, 2022 Oiltanking GmbH, 2025	The mining, survey and support vessel for mining the nodules requires (172+12.8+22.8=) 207.6 kt marine gas oils for 12.47 Mt wet nodules (Benchmark, 2022). So, 21.91 kg marine gas oils for 1.32 tonnes of wet nodules. Assumed is that, marine gas oils are similar to light fuel oil (Oiltanking GmbH, 2025).
Economic flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1,32	t	Wet nodules			CCZ	Planet Tracker, 2023 Benchmark, 2022	It is assumed that 1 tonne of dry nodules requires 1.3158 tonnes of wet nodules, since the moisture content of the nodules is estimated to be 24% for the NORI area (=1+(24/76)=1.3158).
Environmental flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1,32	t	Wet nodules			CCZ	Planet Tracker, 2023 Benchmark, 2022	It is assumed that 1 tonne of dry nodules requires 1.3158 tonnes of wet nodules, since the moisture content of the nodules is estimated to be 24% for the NORI area (=1+(24/76)=1.3158)
165,66	m2	Transformation, from seabed, natural (non-use)			CCZ	Benchmark, 2022	Transformation of the seabed is 1570 km2 for 12.47 Mt wet nodules. So, 165.66 m2 for 1.32 tonnes wet nodules.
165,66	m2	Transformation, to seabed, drilling and mining			CCZ	Benchmark, 2022	Transformation of the seabed is 1570 km2 for 12.47 Mt wet nodules. So, 165.66 m2 for 1.32 tonnes wet nodules.
77,87	m2a	Occupation, seabed, drilling and mining			CCZ	Benchmark, 2022	Occupation of the seabed is 738 km2a for 12.47 Mt wet nodules. So, 77.87 m2a for 1.32 tonnes wet nodules.
Environmental flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
68,99	kg	Carbon dioxide, fossil			CCZ	Benchmark, 2022	542+40.2+71.6 kt for 12.47 Mt wet nodules, so 68.99 kg for 1.32 tonnes wet nodules.
0,64	kg	Sulfur oxides			CCZ	Benchmark, 2022	5.04+0.334+0.65 kt for 12.47 Mt wet nodules, so 0.64 kg for 1.32 tonnes wet nodules.
0,25	kg	Nitrogen oxides			CCZ	Benchmark, 2022	2.01+0.134+0.26 kt for 12.47 Mt wet nodules, so 0.25 kg for 1.32 tonnes wet nodules.
1,80	kg	suspended solids			CCZ	Benchmark, 2022	Proxy for "Mobilised sediment" 17.1 Mt for 12.47 Mt wet nodules, so 1.80 kg for 1.32 tonnes wet nodules.

Unit Process: Offshore Horizontal Transport (P2)							
Economic flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1,32	t	Wet nodules	Collection & Vertical Transport	P1	CCZ		
13460,19	tkm	Transport, freight, sea, bulk carrier for dry goods	market for transport, freight, sea, bulk carrier for dry goods   transport, freight, sea, bulk carrier for dry goods   Cutoff, U - GLO	P7	GLO	Fritz et al., 2023 Gales, 2023	2163 Mtkm for 1120 kt wet nodules, for 1930 km (Fritz et al., 2023) The distance from the CCZ (NORI-D area) to the Hachinohe port in Japan is 5520 nautical miles (Gales, 2023), which is 10223 km because 1 nautical mile is equal to 1.852 km. Therefore,  $\frac{2163000000}{1120000 * 1930} = 1.00065 \text{ tkm/ton/km}$ $1.00065 * 1.3158 * 10223 = 13460.19 \text{ tkm}$
Economic flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1,32	t	Wet nodules			JP		
Environmental flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
Environmental flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation

Unit Process: Pre-Processing & Polymetallurgical Processing (P3)							
Economic flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1,32	t	Wet nodules	Offshore Horizontal Transport	P2	JP		
2033,32	MJ	heat, district or industrial, natural gas	heat production, natural gas, at industrial furnace >100kW   heat, district or industrial, natural gas   Cutoff, U - RoW	P8	RoW	Benchmark, 2022	Proxy for heat from natural gas (Benchmark, 2022). 9.89 PJ for 6.4 Mt wet nodules. So, 2033.32 MJ for 1.32 tonnes of wet nodules. In this flow, the fuel input is already included, so natural gas is not added again as an inflow as is the case in the study of Benchmark (2022).
2261,53	MJ	heat, district or industrial, other than natural gas	heat production, at coal coke industrial furnace 1-10MW   heat, district or industrial, other than natural gas   Cutoff, U - RoW	P9	RoW	Benchmark, 2022	Proxy for heat from coal (Benchmark, 2022). 11 PJ for 6.4 Mt wet nodules. So, 2261.53 MJ for 1.32 tonnes of wet nodules. In this flow, the fuel input is already included, so coal is not added again as an inflow as is the case in the study of Benchmark (2022).
460,40	kWh	electricity, high voltage	electricity, high voltage, production mix   electricity, high voltage   Cutoff, U - JP	P10	JP	Benchmark, 2022	2239.37 GWh for 6.4 Mt wet nodules. So, 460.4 kWh for 1.32 tonnes of wet nodules.
6,37	kg	sulfur	market for sulfur   sulfur   Cutoff, U - GLO	P12	GLO	Benchmark, 2022	31 kt for 6.4 Mt wet nodules. So, 6.37 kg for 1.32 tonnes of wet nodules.
1064,98	kg	tap water	market group for tap water   tap water   Cutoff, U - GLO	P13	GLO	Benchmark, 2022	5.18 hm3 for 6.4 Mt wet nodules. So, 1.065 m3 for 1.32 tonnes of wet nodules. This is about 1065 kg water.
83,68	kg	silica sand	market for silica sand   silica sand   Cutoff, U - GLO	P15	GLO	Benchmark, 2022	Proxy for silica flux. 407 kt for 6.4 Mt wet nodules. So, 83.68 kg for 1.32 tonnes of wet nodules.

Economic flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
24.18	kg	Matte Ni/Cu/Co			JP	Benchmark, 2022 SMM, 2025a SMM, 2025c SMM, 2025d	<p>(64.2+48.1+5.29=) 117.59 kt for 6.4 Mt wet nodules (Benchmark, 2022). So, 24.18 kg for 1.32 tonnes of wet nodules.</p> <p><u>For economic allocation:</u> The market value of the matte is based on the market values of the metals within the matte.</p> <p>The market price of nickel is currently about 15152 USD/tonne (SMM, 2025c). Besides, 12.1 kg nickel cathode comes out of the matte (see next process).</p> <p>The market price of cobalt powder is currently about 31704 USD/tonne (SMM, 2025a). Besides, 1.7 kg cobalt comes out of the matte (see next process).</p> <p>The market price of copper cathode is currently about 9648 USD/mt (SMM, 2025d). Besides, 9.27 kg copper, cathode comes out of the matte (see next proces).</p> <p>So, the economic value of the matte is:  <math>((12.1/(12.1+1.7+9.27)*15152+1.7/(12.1+1.7+9.27)*31704+9.27/(12.1+1.7+9.27)*9648)/1000*24.18=)</math> <b>342.4 USD</b> for 24.18 kg matte.</p>
768.92	kg	MnSi slag			JP	Benchmark, 2022 SMM, 2025b	<p>3.74 Mt for 6.4 Mt wet nodules (Benchmark, 2022). So, 768.92 kg for 1.32 tonnes of wet nodules.</p> <p><u>For economic allocation:</u> The market value of SiMn alloy is about 700 USD/tonne (SMM, 2025b). So, the economic value of the MnSi slag is assumed to be <math>(700/1000*768.92=)</math> <b>538.24 USD</b> for 768.92 kg slag.</p>
103.41	kg	gravel, crushed	market for gravel, crushed   gravel, crushed   Cutoff, U - RoW	P22	RoW	Benchmark, 2022	<p>Benchmark (2022) assumed that the converter slag will be used as gravel, so it is an avoided product. 503 kt for 6.4 Mt wet nodules, so 103.41 kg for 1.32 tonnes of wet nodules.</p>
Environmental flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
Environmental flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1.06	m3	Water			JP	Benchmark, 2022	<p>5.18 Mt for 6.4 Mt wet nodules (Benchmark, 2022). So, 1064.98 kg for 1.32 tonnes of wet nodules. This is about 1.06 m3 water. Benchmark (2022) reported 5.18 Gt instead of 5.18 Mt but this has to be a mistake because of the mass balance.</p>

Unit Process: Hydrometallurgical Processing (P4)							
Economic flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
24,18	kg	Matte Ni/Cu/Co	Pre-Processing & Polymetallurgical Processing	P3	JP	Benchmark, 2022 Fritz et al., 2023	<p>24,18 kg matte Ni/Cu/Co comes from 1.32 tonnes of wet nodules according to Benchmark (2022) (see process above). Therefore, the inputs for this hydrometallurgical process are based on 1.32 tonnes wet nodules according to Fritz et al. (2023). Further, the flows of this process are based on the in- and outputs of the processes of Fritz et al. (2023) after the pyrometallurgical processing when the Ni-Cu-Co matte is formed. As stated by Fritz et al. (2023): "Reoxidizing and sulfurizing the Ni-Cu-Co rich forms a matte". So the process in the following red area in the flowchart of Fritz et al. (2023) are included:</p>  <p>The following inputs of Fritz et al. (2023) for processing are assumed to be inputs for the processes outside the red area of the flowchart and are therefore excluded from this hydrometallurgical process: oxygen, gypsum, hard coal, silica sand, heavy fuel oil, graphite, coke, chlorine, carbon black.</p>
10,14	kg	ammonia, anhydrous, liquid	market for ammonia, anhydrous, liquid   ammonia, anhydrous, liquid   Cutoff, U - CN	P16	CN	Fritz et al., 2023	<p>Ammonia is used in the pH adjustment and later recovered in the ammonia recovery process. 8.63 kt for 1120 kt wet nodules, so 10.14 kg for 1.32 tonnes wet nodules. This process, for which ammonia is the input, takes place in Japan, but this region is not available in Ecoinvent for the corresponding background process. China is assumed to be most suitable as a proxy due to its geographical proximity.</p>
0,04	kg	boric acid, anhydrous, powder	market for boric acid, anhydrous, powder   boric acid, anhydrous, powder   Cutoff, U - GLO	P11	GLO	Fritz et al., 2023	<p>Boric acid is used in recovery processes/leaching. 0.036 kt for 1120 kt wet nodules, so 0.04 kg for 1.32 tonnes wet nodules.</p>
199,85	kWh	electricity, high voltage	electricity, high voltage, production mix   electricity, high voltage   Cutoff, U - JP	P10	JP	Fritz et al., 2023	<p>Electricity is used for electrowinning, ion exchange, pumping and mixing. Total electricity input for processing (for pyro+hydro) is 562 GWh for 1120 kt wet nodules, so 660 kWh for 1.32 tonnes wet nodules. The electricity input for hydrometallurgical processing is assumed to be the total amount of electricity input for processing minus the electricity input of the processes "Pre-Processing &amp; Polymetallurgical Processing" above.</p>
0,10	kg	hydrogen, gaseous, medium pressure, merchant	market for hydrogen, gaseous, medium pressure, merchant   hydrogen, gaseous, medium	P18	RoW	Fritz et al., 2023	<p>Hydrogen is used in cobalt recovery. 0.087 kt for 1120 kt wet nodules, so 0.10 kg for 1.32 tonnes wet nodules.</p>
1,28	kg	hydrogen sulfide	market for hydrogen sulfide   hydrogen sulfide   Cutoff, U - RoW	P19	RoW	Fritz et al., 2023	<p>Hydrogen sulfide is used in copper liquid ion exchange and cobalt recovery. 1.09 kt for 1120 kt wet nodules, so 1.28 kg for 1.32 tonnes wet nodules.</p>
22,91	kg	lime, packed	market for lime, packed   lime, packed   Cutoff, U - RoW	P20	RoW	Fritz et al., 2023	<p>Lime is used for neutralization. 19.5 kt for 1120 kt wet nodules, so 22.91 kg for 1.32 tonnes wet nodules.</p>

3,95	kg	nitrogen, liquid	market for nitrogen, liquid   nitrogen, liquid   Cutoff, U - RoW	P21	RoW	Fritz et al., 2023	Nitrogen is used for ammonia recovery. 3.36 kt for 1120 kt wet nodules, so 3.95 kg for 1.32 tonnes wet nodules.
0,08	kg	polyacrylamide	market for polyacrylamide   polyacrylamide   Cutoff, U - GLO	P23	GLO	Fritz et al., 2023	Polyacrylamide is used for waste treatment. 0.064 kt for 1120 kt wet nodules, so 0.08 kg for 1.32 tonnes wet nodules.
30,90	kg	quicklime, milled, packed	market for quicklime, milled, packed   quicklime, milled, packed   Cutoff, U - RoW	P14	RoW	Fritz et al., 2023	Quicklime is used for neutralization. 26.3 kt for 1120 kt wet nodules, so 30.90 kg for 1.32 tonnes wet nodules.
0,26	kg	sodium sulfate, anhydrite	market for sodium sulfate, anhydrite   sodium sulfate, anhydrite   Cutoff, U - RoW	P24	RoW	Fritz et al., 2023	Sodium sulfate is used for ion exchange. 0.22 kt for 1120 kt wet nodules, so 0.26 kg for 1.32 tonnes wet nodules.
0,04	kg	sodium chloride	market for sodium chloride, powder   sodium chloride, powder   Cutoff, U - GLO	P17	GLO	Fritz et al., 2023	Sodium chloride is used for ion exchange. 0.036 kt for 1120 kt wet nodules, so 0.04 kg for 1.32 tonnes wet nodules.
29,25	kg	sulfuric acid	market for sulfuric acid   sulfuric acid   Cutoff, U - RoW	P25	RoW	Fritz et al., 2023	Sulfuric acid is used in leaching. 24.9 kt for 1120 kt wet nodules, so 29.25 kg for 1.32 tonnes wet nodules.
2060,05	kg	tap water	market group for tap water   tap water   Cutoff, U - GLO	P13	RoW	Fritz et al., 2023	The water input is assumed to be the total amount of water input for processing of Fritz et al. (2023) minus the water input of the processes "Pre-Processing & Polymetallurgical Processing " above. Total water input is 2.66 Mt for 1120 kt wet nodules, so 3125 kg for 1.32 tonnes wet nodules.
<b>Economic flows, out:</b>							
<i>Amount</i>	<i>Unit</i>	<i>Flow name</i>	<i>Provider</i>	<i>P-number</i>	<i>Location</i>	<i>Data source</i>	<i>Additional documentation</i>
12,10	kg	nickel, cathode			JP	Fritz et al., 2023 SMM, 2025c	10.3 kt for 1120 kt wet nodules, so 12.10 kg for 1.32 tonnes wet nodules.  <u>For economic allocation:</u> The market price of nickel is currently about 15152 USD/tonne (SMM, 2025c). So, the economic value of this flow becomes $(12.1 * 15152 / 1000) = 183.35$ USD
1,70	kg	cobalt-powder			JP	Fritz et al., 2023 SMM, 2025a	1.45 kt for 1120 kt wet nodules, so 1.70 kg for 1.32 tonnes wet nodules.  <u>For economic allocation:</u> The market price of cobalt powder is currently about 31704 USD/tonne (SMM, 2025a).
9,27	kg	copper, cathode			JP	Fritz et al., 2023 SMM, 2025d	7.89 kt for 1120 kt wet nodules, so 9.27 kg for 1.32 tonnes wet nodules.  <u>For economic allocation:</u> The market price of copper cathode is currently about 9648 USD/mt (SMM, 2025d). So, the economic value of this flow becomes $(9.27 * 9648 / 1000) = 89.43$ USD
261,99	kg	inert waste, for final disposal	market for inert waste, for final disposal   inert waste, for final disposal   Cutoff, U - RoW	P26	RoW	Fritz et al., 2023	446 kt for 1120 kt wet nodules, so 523.97 kg for 1.32 tonnes wet nodules. However, this is for both before and after the Ni-Cu-Co matte phase. Therefore, assumed is that it is 1/2 of the total inert waste.
<b>Environmental flows, in:</b>							
<i>Amount</i>	<i>Unit</i>	<i>Flow name</i>	<i>Provider</i>	<i>P-number</i>	<i>Location</i>	<i>Data source</i>	<i>Additional documentation</i>
<b>Environmental flows, out:</b>							
<i>Amount</i>	<i>Unit</i>	<i>Flow name</i>	<i>Provider</i>	<i>P-number</i>	<i>Location</i>	<i>Data source</i>	<i>Additional documentation</i>
2,06	m3	Water			JP	Fritz et al., 2023	Fritz et al. (2023) only modelled the outflows that contribute to climate change, so they did not include the emission of water to air. This flow can be calculated with the water inflow, based on mass-balance. 2060.05 kg water is about 2.06 m3 water.
3,95	kg	Nitrogen			JP	Fritz et al., 2023	Fritz et al. (2023) only modelled the outflows that contribute to climate change, so they did not include the emission of nitrogen to air. This flow can be calculated with the nitrogen inflow, based on mass-balance.

Unit Process: Bucket DSM (P26)							
Economic flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
12,10	kg	nickel, cathode			JP	Fritz et al., 2023	10.3 kt for 1120 kt wet nodules, so 12.10 kg for 1.32 tonnes wet nodules.
1,70	kg	cobalt-powder			JP	Fritz et al., 2023	1.45 kt for 1120 kt wet nodules, so 1.70 kg for 1.32 tonnes wet nodules.
9,27	kg	copper, cathode			JP	Fritz et al., 2023	7.89 kt for 1120 kt wet nodules, so 9.27 kg for 1.32 tonnes wet nodules.
Economic flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
1,00	item	Bucket Ni/Cu/Co			JP		
Environmental flows, in:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
Environmental flows, out:							
Amount	Unit	Flow name	Provider	P-number	Location	Data source	Additional documentation
Sources							
Alvarenga, R., Pr�at, N., Duhayon, C., & Dewulf, J. (2022). Prospective life cycle assessment of metal commodities obtained from deep-sea polymetallic nodules. <i>Journal of Cleaner Production</i> , 330, 129884. <a href="https://doi.org/10.1016/j.jclepro.2021.129884">https://doi.org/10.1016/j.jclepro.2021.129884</a>							
Benchmark Mineral Intelligence. (2022). The metals company - life cycle assessment for TMC's NORI-dpolymetallic nodule project and comparison to key land-based routes for producing nickel, cobalt and copper. <a href="https://metals.co/wp-content/uploads/2023/03/TMC_NORI-D_LCA_Final_Report_March2023.pdf">https://metals.co/wp-content/uploads/2023/03/TMC_NORI-D_LCA_Final_Report_March2023.pdf</a>							
Ecoinvent. (2025). EcoQuery. EcoQuery. <a href="https://ecoquery.ecoinvent.org/3.10.1/cutoff">https://ecoquery.ecoinvent.org/3.10.1/cutoff</a>							
Fritz, B., Heidak, P., Vasters, J., Kuhn, T., Franken, G., & Schmidt, M. (2023). Life cycle impact on climate change caused by metal production from deep sea manganese nodules versus land-based deposits. <i>Resources, Conservation and Recycling</i> , 193, 106976. <a href="https://doi.org/10.1016/j.resconrec.2023.106976">https://doi.org/10.1016/j.resconrec.2023.106976</a>							
Gales, P. (2023). CCZ Logistics. Deep Sea Mining. <a href="https://deepseamining.ac/article/25#gsc.tab=0">https://deepseamining.ac/article/25#gsc.tab=0</a>							
IPCC. (2006). Chapter 2: Stationary combustion. In <i>2006 IPCC Guidelines for National Greenhouse Gas Inventories</i> (p. 2.1-2.5). <a href="https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf">https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf</a>							
Oiltanking GmbH. (2025). Marine Gasoil (MGO). Oiltanking. <a href="https://www.oiltanking.com/en/news-info/glossary/marine-gasoil-mgo.html">https://www.oiltanking.com/en/news-info/glossary/marine-gasoil-mgo.html</a>							
Planet Tracker. (2023). The sky high cost of deep sea mining. <a href="https://planet-tracker.org/wp-content/uploads/2023/06/Deep-Sea-Mining.pdf">https://planet-tracker.org/wp-content/uploads/2023/06/Deep-Sea-Mining.pdf</a>							
SMM. (2025a). Cobalt powder price today. Retrieved May 27, 2025, from <a href="https://www.metal.com/en/prices/201102250186">https://www.metal.com/en/prices/201102250186</a>							
SMM. (2025b). SIMn alloy(6517) - south price today   historical price charts of SIMn alloy(6517) - south - shanghai metal market. Retrieved May 27, 2025, from <a href="https://www.metal.com/en/prices/201205090002">https://www.metal.com/en/prices/201205090002</a>							
SMM. (2025c). SMM #1 nickel price today. Retrieved May 27, 2025, from <a href="https://www.metal.com/Nickel/201102250239">https://www.metal.com/Nickel/201102250239</a>							
SMM. (2025d). SMM 1# copper cathode price today. Retrieved May 27, 2025, from <a href="https://www.metal.com/Copper/201102250376">https://www.metal.com/Copper/201102250376</a>							
Webster, I. (2025). Inflation Rate between 2025-2005   Euro Inflation Calculator. <a href="https://www.in2013dollars.com/europe/inflation/2025?endYear=2005&amp;amount=1">https://www.in2013dollars.com/europe/inflation/2025?endYear=2005&amp;amount=1</a>							
Xe. (2025). 1 USD to EUR - US Dollars to Euros Exchange Rate. <a href="https://www.xe.com/nl/currencyconverter/convert/?Amount=1&amp;From=USD&amp;To=EUR">https://www.xe.com/nl/currencyconverter/convert/?Amount=1&amp;From=USD&amp;To=EUR</a>							

## C.2. Unit-Process Table Land-Based Mining

Unit Process: Nickel, class 1 production (land-mining) (P28)									
Economic flows, in:									
Amount	Unit	Flow name	Provider	P-number	Location	Mine production [t] (USGS, 2025)	% share of country per metal	Changed flows *	Additional documentation
8,20	kg	nickel, class 1	Nickel, class 1 production - <b>Indonesia</b> - ID	P31	ID	2200000		68% - Electricity, medium voltage - Hard coal	New Caledonia was not included as this location is not available in Ecoinvent
1,23	kg	nickel, class 1	Nickel, class 1 production - <b>Philippines</b> - PH	P32	PH	330000		10% - Electricity, medium voltage	
0,78	kg	nickel, class 1	platinum group metal mine operation, ore with high palladium content   nickel, class 1   Cutoff, U -	P33	RU	210000		6%	Ecoinvent has a specific land-mining process for the production of this metal.
0,71	kg	nickel, class 1	Nickel, class 1 production - <b>Canada</b> - CA	P34	CA	190000		6% - Electricity, medium voltage - Heat, natural gas - Heat, other than natural gas - Iron sulfate - Lime - Limestone - Natural gas, low pressure - Nitrogen, liquid - Oxygen, liquid - Quicklime - Sodium hydroxide - steel, low-alloyed - sulfur dioxide - Sulfuric acid - Tap water - Water, decarbonised - Wastewater, average	CA-QC is often chosen, because well presented in Ecoinvent and Quebec is one of the top nickel producing provinces in Canada.
0,45	kg	nickel, class 1	Nickel, class 1 production - <b>China</b> - CN	P36	CN	120000		4% - Ammonia - Ammonia nitrate - Chlorine - Electricity, medium voltage - Hard coal - Heat, other than natural gas - Hydrochloric acid - Natural gas - Nitric acid - Sodium sulfate - Sulfur - Sulfuric acid - Transport, freight train - Water, decarbonised	
0,41	kg	nickel, class 1	Nickel, class 1 production - <b>Australia</b> - AU	P35	AU	110000		3% - Electricity, medium voltage - Hard coal - Heat, natural gas - Heat, other than natural gas	

0,29	kg	nickel, class 1	Nickel, class 1 production - <b>Brazil</b> - BR	P37	BR	77000	2%	<ul style="list-style-type: none"> <li>- Diesel</li> <li>- Electricity, medium voltage</li> <li>- Heat, other than natural gas</li> <li>- Heavy fuel oil</li> <li>- Kerosene</li> <li>- Light fuel oil</li> <li>- Naphta</li> <li>- Sulfur</li> <li>- Tap water</li> <li>- Transport, freight, lorry, unspecified</li> <li>- Water, decarbonised</li> <li>- Inert waste</li> <li>- Nickel smelter slag</li> <li>- Waste mineral oil</li> </ul>	
0,03	kg	nickel, class 1	Nickel, class 1 production - <b>United States</b> - US	P38	US	8000	0%	<ul style="list-style-type: none"> <li>- Electricity, medium voltage</li> <li>- Heat, natural gas</li> <li>- Heat, other than natural gas</li> <li>- Hydrogen</li> <li>- Natural gas</li> <li>- Sulfur</li> <li>- Transport, freight train</li> <li>- Water, decarbonised</li> <li>- Inert waste</li> <li>- Waste mineral oil</li> </ul>	
<b>Economic flows, out:</b>									
<i>Amount</i>	<i>Unit</i>	<i>Flowname</i>	<i>Provider</i>	<i>P-number</i>	<i>Location</i>				<i>Additional documentation</i>
12,10	kg	nickel, class 1							



Unit Process: Cobalt production (land-mining) (P30)									
Economic flows, in:									
Amount	Unit	Flow name	Provider	F-number	Location	Mine production [t] (USGS, 2022, % share of country per metal)	Changed flows*	Additional documentation	
0,74	kg	cobalt	Cobalt production - <b>Congo (Kinshasa)</b> -	P52	CD	220000	44%	- Electricity	
0,09	kg	cobalt	Cobalt production - <b>Indonesia</b> - CD	P53	ID	28000	6%	- Electricity - Hard coal	
0,03	kg	cobalt	Cobalt production - <b>Russia</b> - RU	P54	RU	8700	2%	- Electricity - Ammonia - Hard coal - Heat, natural gas - Nitric acid - Sulfuric acid - Water, decarbonised	
0,84	kg	cobalt	Cobalt production - <b>China</b> - CN	P55	CN	248000	49%	- Ammonia - Ammonium nitrate - Chlorine, liquid - Electricity - Hard coal - Heat, other than natural gas - Hydrochloric acid - Natural gas - Nitric acid - Sodium sulfate - Sulfur - Sulfuric acid - Transport, freight train - Water decarbonised	China dominates the global cobalt refining and the majority of the cobalt that China refines comes from the cobalt mined in Congo (DRC) and Indonesia. Therefore, China is included as cobalt production location in the same size as Congo (DRC) and Indonesia together.
Economic flows, out:									
Amount	Unit	Flow name	Provider	F-number	Location			Additional documentation	
1,70	kg	cobalt							

\* The initial Ecoinvent background processes for global metal production are transformed into foreground processes by changing the location of the background processes of the flows in this process.  
If the location was available for the flows, the location was changed, otherwise the flows were kept the same as in the global average background process of Ecoinvent.

### C.3. P-Numbers

Number	Process Name
P1	Collection & Vertical Transport
P2	Offshore Horizontal Transport
P3	Pre-Processing & Pyrometallurgical Processing
P4	Hydrometallurgical Processing
P6	market for light fuel oil   light fuel oil   Cutoff, U - RoW
P7	market for transport, freight, sea, bulk carrier for dry goods   transport, freight, sea, bulk carrier for dry goods   Cutoff, U - GLO
P8	heat production, natural gas, at industrial furnace >100kW   heat, district or industrial, natural gas   Cutoff, U - RoW
P9	heat production, at coal coke industrial furnace 1-10MW   heat, district or industrial, other than natural gas   Cutoff, U - RoW
P10	electricity, high voltage, production mix   electricity, high voltage   Cutoff, U - JP
P11	market for boric acid, anhydrous, powder   boric acid, anhydrous, powder   Cutoff, U - GLO
P12	market for sulfur   sulfur   Cutoff, U - GLO
P13	market group for tap water   tap water   Cutoff, U - GLO
P14	market for quicklime, milled, packed   quicklime, milled, packed   Cutoff, U - RoW
P15	market for silica sand   silica sand   Cutoff, U - GLO
P16	market for ammonia, anhydrous, liquid   ammonia, anhydrous, liquid   Cutoff, U - CN
P17	market for sodium chloride, powder   sodium chloride, powder   Cutoff, U - GLO
P18	market for hydrogen, gaseous, medium pressure, merchant   hydrogen, gaseous, medium pressure, merchant   Cutoff, U - RoW
P19	market for hydrogen sulfide   hydrogen sulfide   Cutoff, U - RoW
P20	market for lime, packed   lime, packed   Cutoff, U - RoW
P21	market for nitrogen, liquid   nitrogen, liquid   Cutoff, U - RoW
P22	market for gravel, crushed   gravel, crushed   Cutoff, U - RoW
P23	market for polyacrylamide   polyacrylamide   Cutoff, U - GLO
P24	market for sodium sulfate, anhydrite   sodium sulfate, anhydrite   Cutoff, U - RoW
P25	market for sulfuric acid   sulfuric acid   Cutoff, U - RoW
P26	market for inert waste, for final disposal   inert waste, for final disposal   Cutoff, U - RoW
P27	Bucket DSM
P28	Nickel, class 1 production (land-mining)
P29	Copper cathode production (land-mining)
P30	Cobalt production (land-mining)
P31	Nickel, class 1 production - Indonesia - ID
P32	Nickel, class 1 production - Philippines - PH
P33	platinum group metal mine operation, ore with high palladium content   nickel, class 1   Cutoff, U - RU
P34	Nickel, class 1 production - Canada - CA
P35	Nickel, class 1 production - Australia - AU
P36	Nickel, class 1 production - China - CN
P37	Nickel, class 1 production - Brazil - BR
P38	Nickel, class 1 production - United States - US
P39	copper cathode production - Chile - CL
P40	copper cathode production - Peru - PE
P41	copper cathode production - Congo (Kinshasa) - CD
P42	copper cathode production - China - CN
P43	copper cathode production - United States - US
P44	platinum group metal mine operation, ore with high palladium content   copper, cathode   Cutoff, U - RU
P45	copper cathode production - Indonesia - ID
P46	copper cathode production - Australia - AU
P47	copper cathode production - Zambia - ZM
P48	copper cathode production - Mexico - MX
P49	copper cathode production - Kazakhstan - KZ
P50	copper cathode production - Canada - CA
P51	copper cathode production - Poland - PL
P52	Cobalt production - Congo (Kinshasa) - CD
P53	Cobalt production - Indonesia - CD
P54	Cobalt production - Russia - RU
P55	Cobalt production - China - CN
P56	Ni/Co/Cu production from land-mining

# Appendix D: Aligned LCA Results

## D.1. Inventory Analysis

Complete life-cycle inventory table available upon request.

Deep-Sea Alternative – Inventory Analysis Results									
Inputs					Outputs				
Flow U/L	Category	Sub-ca	Unit	Result	Flow U/L	Category	Sub-ca	Unit	Result
a45cd24	Aluminium	Resource	in grounc kg	5,82E-02	e87f039c	1,1,1,2-Tetrafluoroethane	Emission to air	unspecific kg	3,08E-07
6df9ea0f	Anhydrite	Resource	in grounc kg	4,85E-08	fa0c2be4	1,1,1,2-Tetrafluoroethane	Emission to air	high popu kg	1,26E-09
4726218f	Antimony	Resource	in grounc kg	7,92E-07	16fcd4f9	1,1,1,2-Tetrafluoroethane	Emission to air	low popu kg	1,44E-07
8b46f615	Argon	Resource	in air kg	5,88E-02	9b77be3	1,1,1-Trichloroethane	Emission to water	surface w kg	1,82E-18
e16fd15c	Arsenic	Resource	in grounc kg	1,26E-05	9358556	1,1,1-Trichloroethane	Emission to air	low popu kg	2,88E-08
240177df	Barium	Resource	in grounc kg	5,75E-01	c8e5538	1,1,1-Trichloroethane	Emission to water	unspecific kg	3,43E-09
ac3a891f	Basalt	Resource	in grounc kg	7,45E-03	ce6234f	1,1,1-Trichloroethane	Emission to air	unspecific kg	3,22E-11
eead293	Borax	Resource	in grounc kg	3,92E-08	5253e32	1,1,1-Trifluoroethane	Emission to air	low popu kg	6,16E-34
094ded2	Boron	Resource	in grounc kg	1,46E-02	47c12d9	1,1,2-Trichloro-1,2,2-trifluoroethane	Emission to air	low popu kg	3,80E-07
45d6f26f	Bromine	Resource	in water kg	1,06E-05	caafd44f	1,1,2-Trichloro-1,2,2-trifluoroethane	Emission to air	unspecific kg	7,32E-08
bf377e4f	Cadmium	Resource	in grounc kg	2,25E-05	9b13237f	1,1,2-Trichloro-1,2,2-trifluoroethane	Emission to air	high popu kg	3,33E-09
093ee05	Calcite	Resource	in grounc kg	7,93E+01	393d086	1,1-Difluoroethane	Emission to air	high popu kg	1,54E-06
c8fc4197	Calcium	Resource	in grounc kg	2,46E-02	1c4a106c	1,1-Difluoroethane	Emission to air	low popu kg	1,37E-08
cc6a1ab1	Carbon dioxide, in air	Resource	in air kg	1,67E+01	1a5ef7d5	1,3-Dichloropropene	Emission to soil	agricultu kg	2,74E-11
419de3fc	Carbon dioxide, non-fossil, resource correction	Resource	in air kg	-4,62E-01	d691d3f	1,4-Butanediol	Emission to water	surface w kg	5,50E-03
8c2fe75f	Carbon, organic, in soil or biomass stock	Resource	in grounc kg	1,11E-02	38a622c	1,4-Butanediol	Emission to air	high popu kg	2,39E-09
d16c880f	Carnallite	Resource	in water kg	5,20E-04	e452636	1-Pentanol	Emission to water	surface w kg	1,10E-09
bdb1d02f	Cerium	Resource	in grounc kg	2,32E-04	541a823f	1-Pentanol	Emission to air	high popu kg	4,58E-10
e189e2df	Chromium	Resource	in grounc kg	1,87E-02	f3cf9358	1-Pentene	Emission to water	surface w kg	8,32E-10
c5f5aebf	Chrysotile	Resource	in grounc kg	5,28E-03	8cbaa30	1-Pentene	Emission to air	high popu kg	3,60E-10
93806a5	Clay, bentonite	Resource	in grounc kg	7,73E-02	5e98fd6f	2,2,4-Trimethylpentane	Emission to air	unspecific kg	1,48E-10
f7519ca5	Clay, unspecified	Resource	in grounc kg	8,61E-01	3cfafbc5	2,4-D	Emission to water	surface w kg	5,21E-13
024c972	Coal, brown	Resource	in grounc kg	3,01E+00	e6137e6	2,4-D	Emission to air	low popu kg	2,93E-07
b6d0042	Coal, hard	Resource	in grounc kg	1,46E+02	f681eb3c	2,4-D	Emission to soil	agricultu kg	3,86E-06
d0779a5	Cobalt	Resource	in grounc kg	6,53E-04	9b225d4	2,4-D	Emission to soil	forestry kg	1,15E-08
a9ac40a	Copper	Resource	in grounc kg	1,84E-01	babb6b4	2,4-D	Emission to water	ground w kg	6,50E-08
9877ce0	Diatomite	Resource	in grounc kg	4,43E-09	63e7621	2,4-D	Emission to water	unspecific kg	6,82E-10
c7aee98	Dolomite	Resource	in grounc kg	4,25E-02	b6b4201	2,4-D dimethylamine salt	Emission to air	low popu kg	1,09E-18
9e28eac	Dysprosium	Resource	in grounc kg	2,21E-07	41a4e1fe	2,4-D dimethylamine salt	Emission to soil	agricultu kg	1,84E-08
8bc09c0	Energy, geothermal, converted	Resource	in grounc MJ	2,94E+01	e36c124	2,4-D dimethylamine salt	Emission to water	ground w kg	5,72E-18
01c12fca	Energy, gross calorific value, in biomass	Resource	biotic MJ	1,84E+02	b8db78x	2,4-D dimethylamine salt	Emission to water	surface w kg	2,35E-20
8842042	Energy, gross calorific value, in biomass, primary forest	Resource	biotic MJ	2,07E-01	99e1284	2,4-D ester	Emission to air	low popu kg	1,54E-18
57c71b2f	Energy, kinetic (in wind), converted	Resource	in air MJ	2,56E+01	6986913	2,4-D ester	Emission to soil	agricultu kg	1,41E-10
c0dd7cc	Energy, potential (in hydropower reservoir), converted	Resource	in water MJ	1,82E+02	69bb7dd	2,4-D ester	Emission to water	ground w kg	5,20E-18
a7ff17d4	Energy, solar, converted	Resource	in air MJ	3,83E-01	e636787	2,4-D ester	Emission to water	surface w kg	2,13E-20
110a04f0	Erbium	Resource	in grounc kg	4,42E-08	0b2a860	2,4-DB	Emission to air	low popu kg	1,50E-18
3d73ec2	Europium	Resource	in grounc kg	9,86E-07	d051c44	2,4-DB	Emission to soil	agricultu kg	1,20E-16
26296e0	Feldspar	Resource	in grounc kg	3,37E-11	68f64fd1	2,4-DB	Emission to water	ground w kg	3,66E-18
55219a6f	Fish, demersal, in ocean	Resource	biotic kg	3,89E-27	0513606f	2,4-DB	Emission to water	surface w kg	1,50E-20
d22719df	Fish, pelagic, in ocean	Resource	biotic kg	4,23E-17	d45eed0	2,4-Dichlorophenol	Emission to air	unspecific kg	1,20E-09

Land-Mining Alternative - Inventory Analysis Results

Inputs					Outputs						
Flow UJ	Flow	Category	Sub-ca	Unit	Result	Flow UU	Flow	Category	Sub-ca	Unit	Result
a45cd24	Aluminium	Resource	in ground	kg	9.97E+00	e87f039d	1,1,1,2-Tetrafluoroethane	Emission to air	unspecifi	kg	1.04E-06
6df9ea0f	Anhydrite	Resource	in ground	kg	3.49E-07	fa0c2bee	1,1,1,2-Tetrafluoroethane	Emission to air	high popu	kg	1.53E-08
47262181	Antimony	Resource	in ground	kg	1.10E-06	16fd4f9-	1,1,1,2-Tetrafluoroethane	Emission to air	low popu	kg	2.41E-07
8b46161e	Argon	Resource	in air	kg	9.42E-02	9b77be3f	1,1,1-Trichloroethane	Emission to water	surface v	kg	2.69E-17
e16fd15c	Arsenic	Resource	in ground	kg	2.24E-02	9958556c	1,1,1-Trichloroethane	Emission to air	low popu	kg	6.75E-07
240177d1	Barium	Resource	in ground	kg	1.63E+00	c8e5538f	1,1,1-Trichloroethane	Emission to water	unspecifi	kg	5.16E-09
ac3a891f	Basalt	Resource	in ground	kg	9.18E-02	ce6294f5	1,1,1-Trichloroethane	Emission to air	unspecifi	kg	6.03E-10
eead293	Borax	Resource	in ground	kg	2.36E-08	5253e32f	1,1,1-Trifluoroethane	Emission to air	low popu	kg	9.12E-34
094ded2	Boron	Resource	in ground	kg	2.45E-03	47c12d9f	1,1,2-trifluoroethane	Emission to air	low popu	kg	1.21E-07
45d6f26f	Bromine	Resource	in water	kg	3.95E-05	caafd448	1,1,2-Trichloro-1,2,2-trifluoroethane	Emission to air	unspecifi	kg	5.86E-08
bf377e4f	Cadmium	Resource	in ground	kg	4.34E-05	9b132374	1,1,2-Trichloro-1,2,2-trifluoroethane	Emission to air	high popu	kg	8.45E-09
093ee05	Calcite	Resource	in ground	kg	5.92E+01	933d086f	1,1-Difluoroethane	Emission to air	high popu	kg	1.02E-05
c8fc4197	Calcium	Resource	in ground	kg	1.46E+00	1c4a106a	1,1-Difluoroethane	Emission to air	low popu	kg	1.92E-08
co6af1ab1	Carbon dioxide, in air	Resource	in air	kg	2.39E+01	1a5ef7d9	1,3-Dichloropropene	Emission to soil	agricultu	kg	2.19E-10
419de9fc	Carbon dioxide, non-fossil, resource correcti	Resource	in air	kg	8.15E-01	d6911d36	1,4-Butanediol	Emission to water	surface v	kg	3.06E-08
8c2fe75f	Carbon, organic, in soil or biomass stock	Resource	in ground	kg	2.48E-02	38a622cf	1,4-Butanediol	Emission to air	high popu	kg	1.33E-08
d16c880f	Carnallite	Resource	in water	kg	4.39E-03	e452636f	1-Pentanol	Emission to water	surface v	kg	3.54E-09
bdb1d02	Cerium	Resource	in ground	kg	7.21E-04	541a823c	1-Pentanol	Emission to air	high popu	kg	1.47E-09
e183e2d	Chromium	Resource	in ground	kg	3.51E+00	f3cf9958-	1-Pentene	Emission to water	surface v	kg	2.67E-09
c5f5aebf	Chrysotile	Resource	in ground	kg	6.55E-04	8cbaa90f	1-Pentene	Emission to air	high popu	kg	1.64E-08
93806a5	Clay, bentonite	Resource	in ground	kg	2.57E-01	5e98fd60	2,2,4-Trimethylpentane	Emission to air	unspecifi	kg	1.38E-10
f7519ca5	Clay, unspecified	Resource	in ground	kg	1.20E+01	3cfa1bc5-	2,4-D	Emission to water	surface v	kg	2.83E-13
024c972	Coal, brown	Resource	in ground	kg	1.50E+03	e6137e6e	2,4-D	Emission to air	low popu	kg	7.24E-07
b6d0042	Coal, hard	Resource	in ground	kg	2.37E+02	f681eb3c	2,4-D	Emission to soil	agricultu	kg	7.37E-06
d0779a5	Cobalt	Resource	in ground	kg	1.04E+00	9b225d4c	2,4-D	Emission to soil	forestry	kg	2.83E-08
a9ac40a	Copper	Resource	in ground	kg	3.58E+01	babb6b4f	2,4-D	Emission to water	ground w	kg	1.61E-07
9877ce0	Diatomite	Resource	in ground	kg	1.34E-08	63e76211	2,4-D	Emission to water	unspecifi	kg	1.69E-09
c7aee98	Dolomite	Resource	in ground	kg	1.63E-01	b6b4201e	2,4-D dimethylamine salt	Emission to air	low popu	kg	1.06E-17
9e28eac	Dysprosium	Resource	in ground	kg	5.46E-07	41a4e1fe-	2,4-D dimethylamine salt	Emission to soil	agricultu	kg	1.96E-08
8bc09c0	Energy, geothermal, converted	Resource	in ground	MJ	1.49E+03	e36c124e	2,4-D dimethylamine salt	Emission to water	ground w	kg	5.56E-17
01c12fca	Energy, gross calorific value, in biomass	Resource	biotic	MJ	2.56E+02	b8db7f8d	2,4-D dimethylamine salt	Emission to water	surface v	kg	2.28E-19
8842042	Energy, gross calorific value, in biomass, prim.	Resource	biotic	MJ	6.20E-01	99e1284e	2,4-D ester	Emission to air	low popu	kg	1.10E-17
57c71b2f	Energy, kinetic (in wind), converted	Resource	in air	MJ	2.48E+02	6986913c	2,4-D ester	Emission to soil	agricultu	kg	3.10E-10
c0dd7cc	Energy, potential (in hydropower reservoir), cc	Resource	in water	MJ	2.51E+03	69bb7ddf	2,4-D ester	Emission to water	ground w	kg	5.23E-17
a7ff17d4	Energy, solar, converted	Resource	in air	MJ	1.20E+00	e636787f	2,4-D ester	Emission to water	surface v	kg	2.15E-19
110a04f0	Erbium	Resource	in ground	kg	8.43E-08	0b2a860f	2,4-DB	Emission to air	low popu	kg	4.52E-18
3d73ec2	Europium	Resource	in ground	kg	3.03E-06	d051c442	2,4-DB	Emission to soil	agricultu	kg	7.00E-16
26296ec	Feldspar	Resource	in ground	kg	9.02E-10	68f64fd1-	2,4-DB	Emission to water	ground w	kg	2.16E-17
55219a6f	Fish, demersal, in ocean	Resource	biotic	kg	5.76E-27	0513606c	2,4-DB	Emission to water	surface v	kg	8.87E-20
d22719df	Fish, pelagic, in ocean	Resource	biotic	kg	6.26E-17	d45eed0f	2,4-Dichlorophenol	Emission to air	unspecifi	kg	3.84E-10
d90d843	Fluorine	Resource	in ground	kg	7.17E-03	e4f501bb-	2,4-Dichlorophenol	Emission to air	high popu	kg	4.19E-09
08a91e7f	Fluorspar	Resource	in ground	kg	1.50E-01	a0fec60d	2-Aminopropanol	Emission to air	high popu	kg	1.52E-09
f55e220f	Gadolinium	Resource	in ground	kg	1.02E-05	96db42bf	2-Aminopropanol	Emission to water	surface v	kg	3.66E-09
0878c1cf	Gallium	Resource	in ground	kg	2.47E-04	60268f3d	2-Chloro-1,1,1,2-tetrafluoroethane	Emission to air	unspecifi	kg	5.86E-08
0d218f74	Gangue	Resource	in ground	kg	6.47E+02	5b1bd93f	2-Chlorophenol	Emission to water	unspecifi	kg	1.91E-10
3ed5f37	Gas, mine, off-gas, process, coal mining	Resource	in ground	m3	2.37E+00	12dde31e	2-Methyl-2-butanol	Emission to water	unspecifi	kg	6.37E-14

## D.2. Characterization Results Baseline

<b>Impact categories</b>	<b>Unit</b>	<b>DSM alternative</b>	<b>Land alternative</b>	<b>% reduction (DSM relative to land)</b>	<b>% reduction (land relative to DSM)</b>
Acidification: terrestrial	kg SO2-Eq	3,08E+00	1,77E+01	-83%	
Climate change	kg CO2-Eq	6,62E+02	2,63E+03	-75%	
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1,27E+01	1,07E+03	-99%	
Ecotoxicity: marine	kg 1,4-DCB-Eq	1,70E+01	1,34E+03	-99%	
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	8,12E+02	1,59E+04	-95%	
Energy resources: non-renewable, fossil	kg oil-Eq	1,59E+02	6,49E+02	-76%	
Eutrophication: freshwater	kg P-Eq	1,06E-01	4,76E+00	-98%	
Eutrophication: marine	kg N-Eq	1,22E-02	3,22E-01	-96%	
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	4,68E+01	4,11E+02	-89%	
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	3,44E+02	1,41E+04	-98%	
Ionising radiation	kBq Co-60-Eq	1,65E+01	4,53E+01	-64%	
Land use	m2*a crop-Eq	1,11E+01	2,72E+01	-59%	
Material resources: metals/minerals	kg Cu-Eq	3,65E+00	1,50E+02	-98%	
Ozone depletion	kg CFC-11-Eq	1,10E-04	8,30E-04	-87%	
Particulate matter formation	kg PM2,5-Eq	1,06E+00	4,37E+01	-98%	
Photochemical oxidant formation: human health	kg NOx-Eq	1,76E+00	7,71E+00	-77%	
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq	1,80E+00	7,84E+00	-77%	
Water use	m3	4,50E+00	1,42E+01	-68%	
Transformation natural land	m2	6,48E+01	5,72E-01		-99%
Incl. Transformation seabed	m2	6,44E+01	2,25E-02		-100%

## D.3. Scenarios Electricity Sources

### D.3.1. Electricity Source Processing Nodules

Sensitivity analysis of electricity source processing nodules											
Impact categories	Unit	DSM - Japanese mix (base)	DSM - Indian mix	DSM - Indonesian mix	DSM - Malaysian mix	DSM - Mexican mix	DSM - Texan mix	DSM - Hydro	DSM - Nuclear	DSM - Wind	Land-mining
Acidification: terrestrial	kg SO2-Eq	3,08E+00	3,94E+00	3,67E+00	3,30E+00	2,90E+00	2,54E+00	2,27E+00	2,28E+00	2,29E+00	1,77E+01
Climate change	kg CO2-Eq	6,62E+02	9,40E+02	8,30E+02	7,16E+02	6,18E+02	5,80E+02	4,07E+02	4,07E+02	4,11E+02	2,63E+03
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1,27E+01	2,52E+01	3,02E+01	1,62E+01	1,21E+01	1,49E+01	1,05E+01	1,09E+01	1,35E+01	1,07E+03
Ecotoxicity: marine	kg 1,4-DCB-Eq	1,70E+01	3,44E+01	4,10E+01	2,19E+01	1,63E+01	1,99E+01	1,40E+01	1,45E+01	1,76E+01	1,34E+03
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	8,12E+02	1,01E+03	8,70E+02	8,35E+02	9,52E+02	7,47E+02	6,96E+02	7,96E+02	7,36E+02	1,59E+04
Energy resources: non-renewable, fossil	kg oil-Eq	1,59E+02	2,26E+02	1,92E+02	1,59E+02	1,17E+02	1,44E+02	8,99E+01	9,01E+01	9,12E+01	6,49E+02
Eutrophication: freshwater	kg P-Eq	1,06E-01	5,27E-01	8,38E-01	1,97E-01	9,17E-02	1,91E-01	5,65E-02	5,76E-02	5,88E-02	4,76E+00
Eutrophication: marine	kg N-Eq	1,22E-02	3,51E-02	5,54E-02	1,50E-02	1,10E-02	1,52E-02	6,11E-03	6,19E-03	6,32E-03	3,22E-01
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	4,68E+01	9,39E+01	7,71E+01	6,48E+01	4,59E+01	5,01E+01	3,61E+01	3,64E+01	5,13E+01	4,11E+02
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	3,44E+02	1,01E+03	1,04E+03	5,46E+02	3,25E+02	4,20E+02	2,67E+02	3,00E+02	2,82E+02	1,41E+04
Ionising radiation	kBq Co-60-Eq	1,65E+01	3,15E+00	3,04E+00	2,72E+00	1,27E+01	3,12E+01	2,48E+00	2,65E+02	2,66E+00	4,53E+01
Land use	m2*a crop-Eq	1,11E+01	1,10E+01	4,96E+00	7,09E+00	4,78E+00	5,27E+00	4,40E+00	4,45E+00	4,83E+00	2,72E+01
Material resources: metals/minerals	kg Cu-Eq	3,65E+00	3,00E+00	2,98E+00	2,92E+00	3,32E+00	3,24E+00	2,54E+00	2,81E+00	3,36E+00	1,50E+02
Ozone depletion	kg CFC-11-Eq	1,10E-04	1,50E-04	1,30E-04	1,10E-04	1,20E-04	8,77E-05	5,45E-05	5,51E-05	5,55E-05	8,30E-04
Particulate matter formation	kg PM2.5-Eq	1,06E+00	2,14E+00	1,08E+01	1,61E+00	1,07E+00	1,24E+00	7,90E-01	7,96E-01	7,99E-01	4,37E+01
Photochemical oxidant formation: human health	kg NOx-Eq	1,76E+00	2,42E+00	2,39E+00	1,75E+00	1,65E+00	1,40E+00	1,25E+00	1,26E+00	1,26E+00	7,71E+00
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq	1,80E+00	2,46E+00	2,44E+00	1,79E+00	1,71E+00	1,45E+00	1,28E+00	1,29E+00	1,30E+00	7,84E+00
Water use	m3	4,50E+00	5,20E+00	5,41E+00	6,12E+00	4,22E+00	4,28E+00	1,49E+01	4,97E+00	3,88E+00	1,42E+01

### D.3.2. Electricity Source Land-Based Mining

Sensitivity analysis of electricity source in the land-mining model													
Impact categories	Unit	DSM	Land - Global top producers (base)	Land - Global Ecoinvent	Land - Chile	Land - China	Land - Denmark	Land - DRC	Land - Indonesia	Land - Norway	Land - Paraguay	Land - Philippines	Land - Russian Federation
Acidification: terrestrial	kg SO2-Eq	3,08E+00	1,77E+01	9,98E+00	1,67E+01	1,81E+01	1,07E+01	9,77E+00	1,97E+01	9,68E+00	9,67E+00	2,10E+01	1,48E+01
Climate change	kg CO2-Eq	6,62E+02	2,63E+03	4,15E+02	1,72E+03	2,79E+03	6,45E+02	3,12E+02	3,31E+03	2,95E+02	2,87E+02	2,71E+03	2,05E+03
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1,27E+01	1,07E+03	9,74E+02	1,01E+03	1,00E+03	9,98E+02	9,72E+02	1,11E+03	9,73E+02	9,72E+02	1,09E+03	1,00E+03
Ecotoxicity: marine	kg 1,4-DCB-Eq	1,70E+01	1,34E+03	1,21E+03	1,26E+03	1,26E+03	1,24E+03	1,21E+03	1,40E+03	1,21E+03	1,21E+03	1,37E+03	1,26E+03
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	8,12E+02	1,59E+04	1,50E+04	1,56E+04	1,61E+04	1,56E+04	1,49E+04	1,61E+04	1,49E+04	1,48E+04	1,59E+04	1,55E+04
Energy resources: non-renewable, fossil	kg oil-Eq	1,59E+02	6,49E+02	1,29E+02	4,97E+02	6,01E+02	1,87E+02	1,01E+02	8,27E+02	9,41E+01	9,31E+01	6,69E+02	6,15E+02
Eutrophication: freshwater	kg P-Eq	1,06E-01	4,76E+00	1,20E+00	2,12E+00	1,59E+00	1,40E+00	1,16E+00	6,73E+00	1,16E+00	1,16E+00	5,78E+00	2,13E+00
Eutrophication: marine	kg N-Eq	1,22E-02	3,22E-01	9,87E-02	1,57E-01	1,25E-01	1,12E-01	9,42E-02	4,45E-01	9,42E-02	9,36E-02	3,80E-01	1,62E-01
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	4,68E+01	4,11E+02	1,89E+02	3,53E+02	4,41E+02	2,42E+02	1,81E+02	4,72E+02	1,83E+02	1,83E+02	4,24E+02	3,21E+02
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	3,44E+02	1,41E+04	1,04E+04	1,20E+04	1,21E+04	1,08E+04	1,03E+04	1,58E+04	1,03E+04	1,03E+04	1,49E+04	1,16E+04
Ionising radiation	kBq Co-60-Eq	1,65E+01	4,53E+01	1,12E+02	7,37E+00	1,06E+02	1,19E+02	5,17E+00	9,47E+00	5,17E+00	5,15E+00	8,68E+00	4,55E+02
Land use	m2*a crop-Eq	1,11E+01	2,72E+01	1,83E+01	2,56E+01	4,50E+01	1,19E+02	1,69E+01	2,08E+01	1,79E+01	1,69E+01	4,30E+01	2,18E+01
Material resources: metals/minerals	kg Cu-Eq	3,65E+00	1,50E+02	1,47E+02	1,51E+02	1,51E+02	1,50E+02	1,47E+02	1,50E+02	1,47E+02	1,47E+02	1,50E+02	1,54E+02
Ozone depletion	kg CFC-11-Eq	1,10E-04	8,30E-04	4,00E-04	6,70E-04	7,50E-04	6,70E-04	3,90E-04	8,80E-04	3,80E-04	3,80E-04	7,80E-04	2,03E-03
Particulate matter formation	kg PM2.5-Eq	1,06E+00	4,37E+01	3,12E+00	2,07E+01	6,65E+00	3,24E+00	2,98E+00	7,38E+01	2,92E+00	2,92E+00	2,03E+01	7,13E+00
Photochemical oxidant formation: human health	kg NOx-Eq	1,76E+00	7,71E+00	1,89E+00	7,85E+00	8,47E+00	2,45E+00	1,73E+00	9,80E+00	1,66E+00	1,66E+00	6,02E+00	4,61E+00
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq	1,80E+00	7,84E+00	1,96E+00	7,99E+00	8,57E+00	2,54E+00	1,79E+00	9,95E+00	1,72E+00	1,72E+00	6,15E+00	4,87E+00
Water use	m3	4,50E+00	1,42E+01	7,99E+01	4,47E+00	8,43E+00	1,88E+01	2,08E+00	1,35E+01	7,36E+01	2,05E+00	6,67E+00	1,63E+01

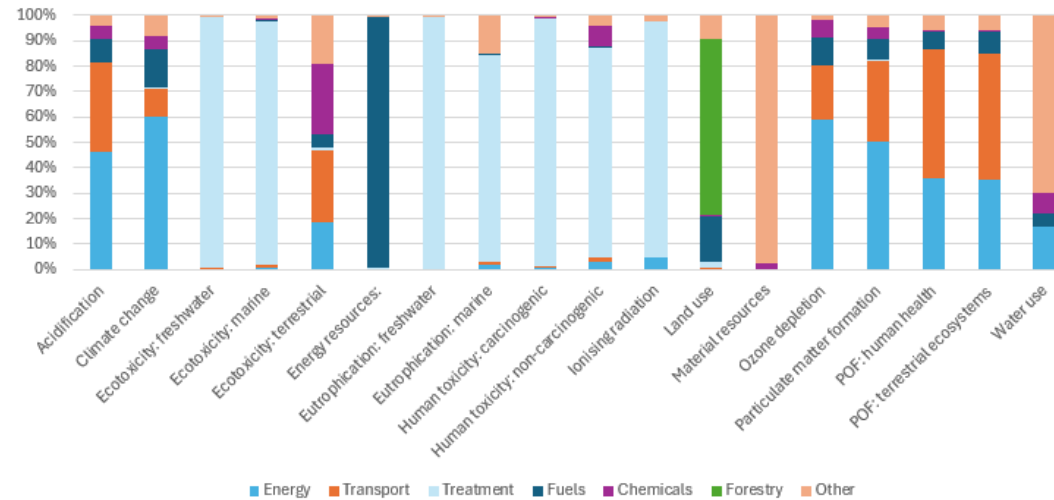
# Appendix E: Contribution Analysis

## E.1. Contribution Phases

Deep-Sea Mining alternative						
Impact categories	Unit	Collection & Vertical transport	Horizontal transport	Pre- & Pyro processing	Hydro processing	
Acidification	kg SO2-Eq	7,84E-01		1,62E+00	-2,32E-01	9,06E-01
Climate change	kg CO2-Eq	8,86E+01		9,79E+01	2,25E+02	2,51E+02
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1,78E-01		1,15E+00	1,93E+00	9,40E+00
Ecotoxicity: marine	kg 1,4-DCB-Eq	2,74E-01		1,66E+00	2,71E+00	1,24E+01
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	3,92E+01		2,34E+02	-3,88E+00	5,43E+02
Energy resources	kg oil-Eq	2,62E+01		2,69E+01	4,96E+01	5,64E+01
Eutrophication: freshwater	kg P-Eq	1,00E-03		3,60E-03	5,32E-02	4,81E-02
Eutrophication: marine	kg N-Eq	4,50E-04		9,00E-04	5,17E-03	5,69E-03
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	2,67E+00		1,81E+01	6,53E+00	1,96E+01
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	4,25E+00		1,59E+01	1,06E+02	2,17E+02
Ionising radiation	kBq Co-60-Eq	1,88E-01		5,39E-01	7,09E+00	8,68E+00
Land use	m2*a crop-Eq	1,84E-01		4,14E-01	4,54E+00	5,92E+00
Material resources	kg Cu-Eq	3,54E-01		1,52E+00	5,65E-03	1,78E+00
Ozone depletion	kg CFC-11-Eq	4,53E-06		4,60E-05	1,54E-05	4,41E-05
Particulate matter formation	kg PM2,5-Eq	2,34E-01		5,22E-01	-1,10E-02	3,20E-01
POF: human health	kg NOx-Eq	3,06E-01		1,51E+00	-5,01E-01	4,44E-01
POF: terrestrial ecosystems	kg NOx-Eq	3,19E-01		1,53E+00	-5,03E-01	4,58E-01
Water use	m3	3,26E-02		8,74E-02	8,27E-01	3,55E+00
Land-Based Mining alternative						
Impact categories	Unit	Cobalt production	Copper production	Nickel production		
Acidification	kg SO2-Eq	1,71E+00	1,89E+00	1,41E+01		
Climate change	kg CO2-Eq	4,07E+02	7,96E+01	2,15E+03		
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	2,38E+01	9,04E+02	1,38E+02		
Ecotoxicity: marine	kg 1,4-DCB-Eq	3,21E+01	1,12E+03	1,89E+02		
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	3,74E+03	6,36E+02	1,15E+04		
Energy resources	kg oil-Eq	9,27E+01	1,92E+01	5,37E+02		
Eutrophication: freshwater	kg P-Eq	1,60E-01	1,07E+00	3,53E+00		
Eutrophication: marine	kg N-Eq	2,98E-02	1,08E-02	2,81E-01		
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	5,65E+01	9,79E+01	2,56E+02		
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	7,84E+02	8,43E+03	4,91E+03		
Ionising radiation	kBq Co-60-Eq	1,48E+01	2,58E+00	2,79E+01		
Land use	m2*a crop-Eq	5,78E+00	7,30E+00	1,41E+01		
Material resources	kg Cu-Eq	3,26E+01	1,55E+01	1,02E+02		
Ozone depletion	kg CFC-11-Eq	1,20E-04	1,30E-04	5,80E-04		
Particulate matter formation	kg PM2,5-Eq	1,59E+00	8,07E-01	4,13E+01		
POF: human health	kg NOx-Eq	1,09E+00	1,10E+00	5,52E+00		
POF: terrestrial ecosystems	kg NOx-Eq	1,11E+00	1,12E+00	5,61E+00		
Water use	m3	1,29E+00	1,61E+00	1,13E+01		

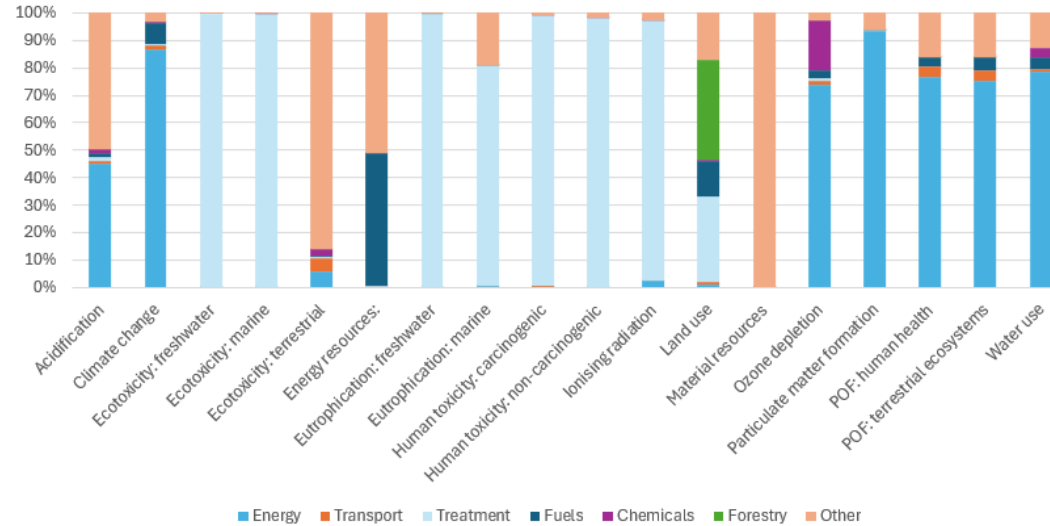
## E.2. Contribution Processes

Contribution of Processes DSM										
		Value is added if process name has one of the following words: electricity, heat.	Value is added if process name has at least one of the following words: transport, freight, car, ship, lorry.	Value is added if process name has the word "treatment".	Value is added if process name has at least one of the following words: coal, gas, petroleum.	Value is added if process name has at least one of the following words: chemical, acid, lime.	Value is added if process name has the word "forest".			
	Unit	Energy	Transport	Treatment	Fuels	Chemicals	Forestry	Other	Total	
Acidification	kg SO2-Eq	1,42E+00	1,08E+00	2,80E-03	2,82E-01	1,68E-01	2,09E-04	1,20E-01	3,08E+00	
Climate change	kg CO2-Eq	3,98E+02	7,13E+01	4,62E+00	1,01E+02	3,40E+01	1,18E-01	5,25E+01	6,62E+02	
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	3,65E-03	9,13E-02	1,25E+01	6,81E-03	3,54E-02	4,62E-07	6,58E-02	1,27E+01	
Ecotoxicity: marine	kg 1,4-DCB-Eq	8,15E-02	2,52E-01	1,63E+01	5,62E-02	1,71E-01	5,20E-05	1,69E-01	1,70E+01	
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	1,51E+02	2,31E+02	9,47E+00	4,10E+01	2,27E+02	1,13E-01	1,53E+02	8,12E+02	
Energy resources:	kg oil-Eq	0,00E+00	4,62E+04	1,16E+00	1,57E+02	7,68E-05	0,00E+00	6,96E-01	1,59E+02	
Eutrophication: freshwater	kg P-Eq	1,70E-06	1,15E-04	1,05E-01	1,68E-05	2,62E-07	1,38E-08	4,44E-04	1,06E-01	
Eutrophication: marine	kg N-Eq	2,07E-04	1,65E-04	9,92E-03	1,01E-04	1,68E-05	4,93E-08	1,80E-03	1,22E-02	
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	1,77E-01	2,88E-01	4,57E+01	4,30E-02	2,62E-01	5,63E-06	3,31E-01	4,68E+01	
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	9,89E+00	5,42E+00	2,84E+02	2,07E+00	2,86E+01	4,34E-04	1,40E+01	3,44E+02	
Ionising radiation	kBq Co-60-Eq	8,20E-01	1,73E-04	1,52E+01	4,43E-03	7,31E-05	0,00E+00	4,20E-01	1,65E+01	
Land use	m2*a crop-Eq	7,25E-03	3,65E-02	2,58E-01	2,00E+00	6,96E-02	7,68E+00	1,01E+00	1,11E+01	
Material resources	kg Cu-Eq	0,00E+00	1,08E-03	0,00E+00	6,12E-04	8,19E-02	0,00E+00	3,57E+00	3,65E+00	
Ozone depletion	kg CFC-11-Eq	6,30E-05	2,27E-05	2,83E-07	1,19E-05	6,84E-06	5,90E-08	2,11E-06	1,07E-04	
Particulate matter formation	kg PM2,5-Eq	5,34E-01	3,41E-01	2,42E-03	8,73E-02	4,98E-02	1,68E-04	4,88E-02	1,06E+00	
POF: human health	kg NOx-Eq	6,30E-01	8,93E-01	4,06E-04	1,20E-01	1,21E-02	5,85E-04	1,01E-01	1,76E+00	
POF: terrestrial ecosystems	kg NOx-Eq	6,32E-01	8,98E-01	4,12E-04	1,56E-01	1,23E-02	5,91E-04	1,04E-01	1,80E+00	
Water use	m3	7,50E-01	3,93E-03	4,55E-04	2,43E-01	3,55E-01	6,84E-08	3,15E+00	4,50E+00	



Contribution of Processes Land-Mining

		Value is added if process name has one of the following words: electricity, heat.	Value is added if process name has at least one of the following words: transport, freight, car, ship, lorry.	Value is added if process name has the word "treatment".	Value is added if process name has at least one of the following words: coal, gas, petroleum.	Value is added if process name has at least one of the following words: chemical, acid, lime.	Value is added if process name has the word "forest".			
	Unit	Energy	Transport	Treatment	Fuels	Chemicals	Forestry	Other	Total	
Acidification	kg SO2-Eq	8,01E+00	1,90E-01	1,98E-01	2,62E-01	2,82E-01	1,93E-04	8,77E+00	1,77E+01	
Climate change	kg CO2-Eq	2,29E+03	3,80E+01	1,18E+01	2,00E+02	9,38E+00	1,12E-01	8,60E+01	2,63E+03	
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	2,01E-02	5,27E-01	1,06E+03	1,39E-02	1,01E-02	-7,09E-07	8,12E-01	1,07E+03	
Ecotoxicity: marine	kg 1,4-DCB-Eq	4,75E-01	1,12E+00	1,33E+03	9,63E-02	2,05E-01	4,32E-05	5,76E+00	1,34E+03	
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	9,12E+02	8,14E+02	5,29E+01	5,61E+01	3,81E+02	9,57E-02	1,36E+04	1,59E+04	
Energy resources:	kg oil-Eq	0,00E+00	7,13E-01	3,08E+00	3,15E+02	3,28E-04	0,00E+00	3,30E+02	6,49E+02	
Eutrophication: freshwater	kg P-Eq	2,33E-05	1,92E-03	4,74E+00	4,13E-05	8,56E-07	1,19E-07	1,71E-02	4,76E+00	
Eutrophication: marine	kg N-Eq	1,57E-03	1,31E-03	2,58E-01	3,32E-04	1,15E-04	4,25E-07	6,10E-02	3,22E-01	
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	6,14E-01	2,91E+00	4,03E+02	6,30E-02	4,36E-01	5,15E-06	3,18E+00	4,11E+02	
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	3,11E+01	2,21E+01	1,38E+04	3,25E+00	5,85E+01	3,34E-04	2,17E+02	1,41E+04	
Ionising radiation	kBq Co-60-Eq	1,09E+00	1,26E-01	4,30E+01	8,61E-03	3,61E-04	0,00E+00	1,15E+00	4,53E+01	
Land use	m2*a crop-Eq	3,50E-01	1,67E-01	8,51E+00	3,49E+00	1,13E-01	9,98E+00	4,62E+00	2,72E+01	
Material resources	kg Cu-Eq	0,00E+00	5,53E-02	0,00E+00	1,97E-03	8,77E-02	0,00E+00	1,50E+02	1,50E+02	
Ozone depletion	kg CFC-11-Eq	6,14E-04	1,15E-05	8,30E-06	2,29E-05	1,49E-04	1,36E-07	2,33E-05	8,29E-04	
Particulate matter formation	kg PM2,5-Eq	4,08E+01	8,63E-02	6,26E-02	8,63E-02	8,02E-02	1,03E-03	2,56E+00	4,37E+01	
POF: human health	kg NOx-Eq	5,90E+00	3,08E-01	1,80E-03	2,54E-01	4,54E-03	5,37E-04	1,24E+00	7,71E+00	
POF: terrestrial ecosystems	kg NOx-Eq	5,91E+00	3,10E-01	1,82E-03	3,49E-01	4,57E-03	5,42E-04	1,27E+00	7,84E+00	
Water use	m3	1,11E+01	1,37E-01	1,10E-02	5,75E-01	4,94E-01	5,82E-07	1,81E+00	1,42E+01	



# Appendix F: Sensitivity Analysis

## F.1. Allocation Method

Sensitivity analysis of allocation method				
<i>From economic allocation to physical allocation</i>				
<b>Impact categories</b>	<b>Unit</b>	<b>DSM alternative (Physical allocation)</b>	<b>Land alternative</b>	<b>% reduction (DSM relative to land)</b>
Acidification: terrestrial	kg SO2-Eq	1,08E+00	1,77E+01	-94%
Climate change	kg CO2-Eq	2,83E+02	2,63E+03	-89%
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	9,66E+00	1,07E+03	-99%
Ecotoxicity: marine	kg 1,4-DCB-Eq	1,27E+01	1,34E+03	-99%
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	5,64E+02	1,59E+04	-96%
Energy resources: non-renewable, fossil	kg oil-Eq	6,44E+01	6,49E+02	-90%
Eutrophication: freshwater	kg P-Eq	5,26E-02	4,76E+00	-99%
Eutrophication: marine	kg N-Eq	6,20E-03	3,22E-01	-98%
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	2,17E+01	4,11E+02	-95%
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	2,27E+02	1,41E+04	-98%
Ionising radiation	kBq Co-60-Eq	9,29E+00	4,53E+01	-80%
Land use	m <sup>2</sup> *a crop-Eq	6,33E+00	2,72E+01	-77%
Material resources: metals/minerals	kg Cu-Eq	1,92E+00	1,50E+02	-99%
Ozone depletion	kg CFC-11-Eq	4,61E-05	8,30E-04	-94%
Particulate matter formation	kg PM2,5-Eq	3,78E-01	4,37E+01	-99%
Photochemical oxidant formation: human health	kg NOx-Eq	5,47E-01	7,71E+00	-93%
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq	5,63E-01	7,84E+00	-93%
Water use	m <sup>3</sup>	3,63E+00	1,42E+01	-74%

## F.2. Market Values

Sensitivity analysis of Market values for economic allocation					
<i>Market values of the metals in the matte from Ecoinvent (5-year average) instead of current prices of SMM.</i>					
	Nickel	Cobalt	Copper	Ni/Cu/Co matte	
Amount [kg]	12,10		1,70	9,27	24,18
Market value SMM [USD]	15,15		31,70	9,65	<b>342,40</b>
Market value Ecoinvent (5-year average) [EUR2005]	12,1		26,5	3,57	
Market value Ecoinvent (5-year average) [EURO2025]*	18,62		40,77	5,49	
Market value Ecoinvent (5-year average) [USD2025]*	20,96		45,91	6,19	<b>407,80</b>
*1 EURO2025 equals 0.65 EURO2005 (Webster, 2025). 1 USD2025 equals 0.888 EURO2025 (Xe, 2025).					
<b>Impact categories</b>	<b>Unit</b>	<b>DSM alternative (Market values Ecoinvent)</b>	<b>Land alternative</b>	<b>% reduction (DSM relative to land)</b>	
Acidification: terrestrial	kg SO2-Eq	3,31E+00	1,77E+01	-81%	
Climate change	kg CO2-Eq	7,06E+02	2,63E+03	-73%	
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1,30E+01	1,07E+03	-99%	
Ecotoxicity: marine	kg 1,4-DCB-Eq	1,75E+01	1,34E+03	-99%	
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	8,41E+02	1,59E+04	-95%	
Energy resources: non-renewable, fossil	kg oil-Eq	1,70E+02	6,49E+02	-74%	
Eutrophication: freshwater	kg P-Eq	1,12E-01	4,76E+00	-98%	
Eutrophication: marine	kg N-Eq	1,29E-02	3,22E-01	-96%	
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	4,98E+01	4,11E+02	-88%	
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	3,57E+02	1,41E+04	-97%	
Ionising radiation	kBq Co-60-Eq	1,73E+01	4,53E+01	-62%	
Land use	m <sup>2</sup> *a crop-Eq	1,16E+01	2,72E+01	-57%	
Material resources: metals/minerals	kg Cu-Eq	3,85E+00	1,50E+02	-97%	
Ozone depletion	kg CFC-11-Eq	1,10E-04	8,30E-04	-87%	
Particulate matter formation	kg PM2,5-Eq	1,15E+00	4,37E+01	-97%	
Photochemical oxidant formation: human health	kg NOx-Eq	1,90E+00	7,71E+00	-75%	
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq	1,95E+00	7,84E+00	-75%	
Water use	m <sup>3</sup>	4,60E+00	1,42E+01	-67%	

### F.3. Impact Assessment Method

Sensitivity analysis of Impact Assessment Method					
EF v3.1 assessment method instead of ReCiPe 2016					
Impact categories	Unit	DSM alternative	Land alternative	% reduction (DSM relative to land)	% reduction (land relative to DSM)
Acidification	mol H+-Eq	4,49E+00	2,53E+01	-82%	
Climate change	kg CO2-Eq	6,49E+02	2,60E+03	-75%	
Climate change: biogenic	kg CO2-Eq	7,50E-01	6,53E+00	-89%	
Climate change: fossil	kg CO2-Eq	6,48E+02	2,59E+03	-75%	
Climate change: land use and land use change	kg CO2-Eq	1,05E-01	5,46E+00	-98%	
Ecotoxicity: freshwater	CTUe	1,22E+03	2,41E+04	-95%	
Ecotoxicity: freshwater, inorganics	CTUe	1,17E+03	2,36E+04	-95%	
Ecotoxicity: freshwater, organics	CTUe	5,03E+01	4,40E+02	-89%	
Energy resources: non-renewable	MJ, net calorific value	7,13E+03	2,86E+04	-75%	
Eutrophication: freshwater	kg P-Eq	1,06E-01	4,76E+00	-98%	
Eutrophication: marine	kg N-Eq	6,82E-01	3,80E+00	-82%	
Eutrophication: terrestrial	mol N-Eq	7,38E+00	3,43E+01	-78%	
Human toxicity: carcinogenic	CTUh	3,23E-07	7,63E-07	-58%	
Human toxicity: carcinogenic, inorganics	CTUh	4,84E-08	6,27E-07	-92%	
Human toxicity: carcinogenic, organics	CTUh	2,74E-07	1,36E-07		-51%
Human toxicity: non-carcinogenic	CTUh	3,87E-06	4,02E-05	-90%	
Human toxicity: non-carcinogenic, inorganics	CTUh	3,67E-06	3,93E-05	-91%	
Human toxicity: non-carcinogenic, organics	CTUh	2,01E-07	8,38E-07	-76%	
Ionising radiation: human health	kBq U235-Eq	2,13E+01	5,83E+01	-63%	
Land use	dimensionless	1,59E+03	3,99E+03	-60%	
Material resources: metals/minerals	kg Sb-Eq	2,43E-03	9,05E-02	-97%	
Ozone depletion	kg CFC-11-Eq	7,48E-06	1,50E-05	-50%	
Particulate matter formation	disease incidence	3,42E-05	2,10E-04	-84%	
Photochemical oxidant formation: human health	kg NMVOC-Eq	2,36E+00	9,96E+00	-76%	
Water use	m3 world Eq deprived	1,93E+02	6,08E+02	-68%	
CML v4.8 Impact Assessment Method					
Impact categories	Unit	DSM alternative	Land alternative	% reduction (DSM relative to land)	
Acidification	kg SO2-Eq	3,50E+00	2,16E+01	-84%	
Climate change	kg CO2-Eq	6,45E+02	2,59E+03	-75%	
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	1,54E+02	9,81E+03	-98%	
Ecotoxicity: marine	kg 1,4-DCB-Eq	5,20E+05	1,40E+07	-96%	
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	2,21E+00	3,21E+02	-99%	
Energy resources: non-renewable	MJ	6,83E+03	2,78E+04	-75%	
Eutrophication	kg PO4-Eq	2,32E+00	1,66E+01	-86%	
Human toxicity	kg 1,4-DCB-Eq	4,97E+02	1,32E+04	-96%	
Material resources: metals/minerals	kg Sb-Eq	2,38E-03	9,03E-02	-97%	
Ozone depletion	kg CFC-11-Eq	6,18E-06	1,23E-05	-50%	
Photochemical oxidant formation	kg ethylene-Eq	1,95E-01	1,01E+00	-81%	

## F.4. Distance Horizontal Transport

Sensitivity analysis of distance horizontal transport									
	Japan	Mexico	India	Malaysia	Texas	Indonesia			
Distance [km]		10223	1930	19524	15450	8751	13455		
Transport, freight, sea, bulk carrier for drygoods		13460	2541	25706	20342	11522	17715		
1 nautical mile =		1,852 km							
Impact categories	Unit	DSM - Japan (base)	DSM - India	DSM - Indonesia	DSM - Malaysia	DSM - Mexico	DSM - Texas	Land-mining	
Acidification: terrestrial	kg SO2-Eq		3,08E+00	3,65E+00	3,27E+00	3,40E+00	2,57E+00	2,98E+00	1,77E+01
Climate change	kg CO2-Eq		6,62E+02	6,96E+02	6,74E+02	6,81E+02	6,31E+02	6,56E+02	2,63E+03
Ecotoxicity: freshwater	kg 1,4-DCB-Eq		1,27E+01	1,31E+01	1,28E+01	1,29E+01	1,23E+01	1,26E+01	1,07E+03
Ecotoxicity: marine	kg 1,4-DCB-Eq		1,70E+01	1,76E+01	1,72E+01	1,73E+01	1,65E+01	1,69E+01	1,34E+03
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq		8,12E+02	8,95E+02	8,41E+02	8,59E+02	7,38E+02	7,99E+02	1,59E+04
Energy resources: non-renewable, fossil	kg oil-Eq		1,59E+02	1,68E+02	1,62E+02	1,64E+02	1,51E+02	1,57E+02	6,49E+02
Eutrophication: freshwater	kg P-Eq		1,06E-01	1,07E-01	1,06E-01	1,07E-01	1,05E-01	1,06E-01	4,76E+00
Eutrophication: marine	kg N-Eq		1,22E-02	1,25E-02	1,23E-02	1,24E-02	1,19E-02	1,22E-02	3,22E-01
Human toxicity: carcinogenic	kg 1,4-DCB-Eq		4,68E+01	5,32E+01	4,90E+01	5,04E+01	4,11E+01	4,58E+01	4,11E+02
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq		3,44E+02	3,49E+02	3,45E+02	3,47E+02	3,39E+02	3,43E+02	1,41E+04
Ionising radiation	kBq Co-60-Eq		1,65E+01	1,67E+01	1,66E+01	1,66E+01	1,63E+01	1,65E+01	4,53E+01
Land use	m2*a crop-Eq		1,11E+01	1,12E+01	1,11E+01	1,11E+01	1,09E+01	1,10E+01	2,72E+01
Material resources: metals/minerals	kg Cu-Eq		3,65E+00	4,19E+00	3,84E+00	3,95E+00	3,17E+00	3,57E+00	1,50E+02
Ozone depletion	kg CFC-11-Eq		1,10E-04	1,20E-04	1,10E-04	1,20E-04	9,23E-05	1,00E-04	8,30E-04
Particulate matter formation	kg PM2,5-Eq		1,06E+00	1,25E+00	1,13E+00	1,17E+00	9,00E-01	1,03E+00	4,37E+01
Photochemical oxidant formation: human health	kg NOx-Eq		1,76E+00	2,29E+00	1,94E+00	2,06E+00	1,28E+00	1,67E+00	7,71E+00
Photochemical oxidant formation: terrestrial ecosystems	kg NOx-Eq		1,80E+00	2,35E+00	1,99E+00	2,11E+00	1,32E+00	1,72E+00	7,84E+00
Water use	m3		4,50E+00	4,53E+00	4,51E+00	4,52E+00	4,47E+00	4,50E+00	1,42E+01