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Prospective life cycle assessment of metal commodities obtained from deep-sea polymetallic nodules

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ABSTRACT

Sustainable metal supply will be essential to achieve climate and sustainability goals (e.g., Paris agreement), for instance by providing the necessary raw materials for renewable energy infrastructure systems. The potential exploitation of mineral resources from the deep sea (e.g., polymetallic nodules) can play a major role in this supply. A holistic environmental analysis is needed, in order to consider the entire value chain of the products obtained out of deep-sea exploitation. Therefore, the objective of this study was to perform a prospective life cycle assessment (LCA) of deep-sea-sourced commodities and compare it to equivalent products obtained from terrestrial mining. It considered as reference flow one tonne of (dry) nodules, using a cradle-to-gate approach up to the final metal commodities, analyzing the delivery to the market of 10.5 kg of copper, 12.8 kg of nickel, 2.3 kg of cobalt and 311.3 kg of ferromanganese. Three environmental impact categories were analyzed, i.e., climate change, acidification and photochemical oxidant formation. Overall, onshore activities (e.g., hydrometallurgical processing) are the main hotspots for environmental impacts of metals sourced from the deep sea; offshore activities play a minor role in the value chain. While photochemical oxidant formation impacts would be similar to terrestrial alternatives, the deep-sea-sourced commodities can bring environmental gains in the order of 38% for climate change and up to 72% for acidification. As this study shows, a strategic selection of the location for onshore processing of the polymetallic nodules is key to target cleaner production, not only because of the distance from the nodules site, but especially because of the available energy mix. The results should be interpreted with care, though, due to intrinsic limitations of the LCA study, e.g., the prospective nature of this study, the limited access to terrestrial mining data, amongst others. Nonetheless, regardless the limitations a prospective LCA imposes, this study highlights some important potential benefits that commodities from deep-sea polymetallic nodules can bring to society with respect to three important environmental impacts.

1. Introduction

The global climate change challenge has initiated an energy transition where new energy sourcing, storage and final use technologies have to be employed, e.g. photovoltaic and wind energy production, storage in stationary batteries and final use in e-mobility. All these technologies that are still under development require specific raw materials. Typical examples are rare earth elements like dysprosium, neodymium and praseodymium in wind energy technology, and lithium and cobalt for battery technology, but also more common raw materials (such as manganese and copper), vital to the current technological developments. Various international bodies like the Organization for Economic Co-operation and Development (OECD) and the European Commission anticipate a huge increase in metal demands. The OECD expects a quadrupling in demand of metals in 2060 (OECD, 2020), whereas the European Commission foresees for example for nickel and cobalt up to a threefold and tenfold growth in demand in 2050, respectively (EC, 2020a).

It is not surprising that the supply of these raw materials poses a lot of sustainability challenges. From an economic point of view, there is the concern of the security of supply that is typically addressed in criticality studies (Schrijvers et al., 2020a,b). This is especially of relevance for economies that are highly dependent on import, like the European Union. Since 2011, the European Commission has made up lists of

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critical raw materials for the European economy. Whereas the first list in 2011 covered 14 raw materials (EC, 2011), the most recent list in 2020 contains 30 (EC, 2020b). Also social impacts associated with their supply are of increasing concern, see for example the study of sustainable sourcing of battery materials where indicators for lack of governance, conflicts, and human and social rights are presented (Mancini et al., 2020). Finally, it is well known that the primary production, including mining and refining, has globally important environmental burdens. Globally, natural resources extraction and processing contribute 50% to the global carbon emissions and even 90% to global biodiversity loss (Oberle et al., 2019).

To ensure the security of metal supply for the energy transition, the potential exploitation of mineral resources from the deep sea (ferromanganese crusts, seafloor massive sulphides and polymetallic nodules) is more than ever discussed (Petersen et al., 2016; Volkmann and Lehnen, 2018; Hein et al., 2020). Discovered in the late nineteenth century, the publication of deep-sea resources estimates in 1965 has shifted polymetallic nodules from geological curiosities to major source of metals for the next generation (Mero, 1965). While they occur in all oceans, the deposits in the Clarion Clipperton Fracture Zone (CCFZ) are considered to be among the richest, containing high grade and high abundance nodules (ISA, 2010). Nodules in the CCZ have more manganese, nickel, cobalt than the entire global terrestrial reserve base for those metals, and significant amounts of copper (Hein et al., 2013). On top of being an additional source of metal supply, the polymetallic nodules can present advantages compared to their terrestrial counterpart. First, with a metal grade (Mn + Ni + Co + Cu) approaching 30% (Hein et al., 2013), their nature is closer to a concentrate than an ore, which decreases the specific energy intensity and impact of their collection, transport and processing purely by mass balance reasons. Second, their comminution characteristics put them in a softer-than-average class of ore (Fuerstenau and Han, 1983, 2003) which is less energy-intensive to mill. Third, once the nodules are collected and ready to bring onshore, there is some flexibility in choosing the location for mineral and metallurgical processing. This selection may consider several criteria, including the distance, the nature of the energy sources, and other environmental, social, ethical and governance aspects. On the other hand, potential impacts on the local biodiversity (Paulikas et al., 2020; Préat et al., 2021) and requirements for technological developments (Paulikas et al., 2020) are some of the challenges faced by these alternative mineral resources. This developing industry requires a clear definition of threshold values, conservation strategies and minimum required management and monitoring programmes in order to avoid serious harm to the marine environment. This requires a clear, transparent, multi-stakeholder and adaptative regulatory process (Watzel et al., 2020). In addition to the environmental risks, the difficulty of international negotiations to reach a legal framework, the issue of common heritage and the roles of sponsoring states and contractors are weaknesses which will be needed to be studied (Leal Filho et al., 2021).

Several exploratory cruises were deployed to access deep-sea minerals wealth (Glasby, 2000; Sparenberg, 2019). Since most of these resources occur beyond exclusive economic zones (EEZ), the United Nations Convention on the Law of the Sea (UNCLOS) was signed in 1982 and came into force in 1994 with the creation of the International Seabed Authority (ISA), an international institution in charge of regulating the exploration and exploitation mineral resources located beyond EEZ (UN, 1994, 1982). Meanwhile, most attention was focused on the Clarion Clipperton Fracture Zone (CCZ), an abyssal area located beyond EEZ in the Eastern Central Pacific, extending on approximately 4.5 million km^2 with depths ranging from 4000 to 6000 m (ISA, 2011). The region is by far the largest potential source of polymetallic nodules discovered until now. Its estimated stocks of cobalt, nickel and manganese are largely exceeding land-based reserves, and its stocks of lithium and copper are about a fourth of land-based reserves (WEF, 2020). So far, the ISA has set up 30 exploration contracts with governments and companies in marine areas containing mineral resources, but no commercial exploitation has been initiated so far. Amongst them, 16 contracts concern exploration areas (75,000 km^2 each) for polymetallic nodules located in the CCZ (ISA, 2020). With rising demand of materials to achieve Paris climate agreement goals (Giurco et al., 2019; Valero et al., 2018), it is not excluded that deep-sea mining operations will supply critical raw materials for the production and storage of renewable energy within the next decade (WEF, 2020). Consequently, the ISA is currently drafting a mining code that can come into force in 2021 for deep-sea minerals exploitation in areas beyond EEZ (ISA, 2019). However, the set-up of a regulatory framework for environmental management of deep-sea mining is constrained by knowledge gaps regarding the impacts of large-scale operations on deep-sea ecosystems (Levin et al., 2020; Tunnicliffe et al., 2020). Regardless of the economic and social aspects, the development of deep-sea mining activities as an alternative to terrestrial mining has uncertain consequences in terms of global environmental sustainability (Beaulieu et al., 2017). It is known that sourcing crucial metals for renewable energy production by intensification of terrestrial mining will induce major threat to biodiversity (Sonter et al., 2020). The question is still open for the development of large scale deep-sea mining, but it is clear it requires a precautionary and step-wise approach focusing on avoiding serious environmental harm and minimize loss of biodiversity (Niner et al., 2018).

The identification of the least harmful option should be made by considering several environmental topics and considering the entire value chain of metal production, from ore body to final commodities, including all mining and refining processes (Alvarenga et al., 2019). Accordingly, the Life Cycle Assessment (LCA) methodology has potential to compare deep-sea resources exploitation with its terrestrial equivalent in addition to impact assessment on *in-situ* ecosystem to assess threats on ecological conditions such as biodiversity (UNEP, 2007). Paulikas et al. (2020) published a comparative LCA to produce crucial materials for electric vehicles (nickel sulphate, cobalt sulphate, manganese sulphate and copper cathode) from polymetallic nodules to be collected in the CCZ and from terrestrial mining. The study focuses on CO_2 equivalent emissions (i.e. impact category *global warming* or *climate change*) from ores extraction to material production (i.e. from cradle to gate) and includes impacts on carbon sequestration. The study highlights that deep-sea mining can perform better than terrestrial mining, with a decrease of 70% of climate change impacts to produce battery materials. Energy requirements for nodules processing were entirely provided by hydroelectricity to process deep-sea minerals while two terrestrial ore processing scenarios were modelled with anticipated electricity mixes from 2015 to 2050. The projections consider gas, oil and coal accounting for approximately 65% in the first scenario while this contribution decreases to approximately 40% in 2050, with coal phase-out in 2045 in the second scenario. The different scenarios were not systematically implemented in both terrestrial and deep-sea mineral processing systems. So far, this study is the only comparative LCA published for deep-sea minerals and highlights the potential of deep-sea minerals sourcing to reduce greenhouses gases emissions from the mining and refining sectors for given electricity mix scenarios. However, other environmental impact categories should also be considered in an LCA study, e.g., acidification (Santero and Hendry, 2016). Therefore, while climate change is covered in Paulikas et al. (2020), there is potential to consider additional impact categories in a comparative LCA of deep-sea mining.

The aim of this study is to perform a comparative LCA of deep-sea polymetallic nodules mining in the CCZ with equivalent production from terrestrial mining in order to benchmark the environmental performance of both options. The comparative assessment focuses on the production of three key metals for the renewable energy transition, copper, nickel and cobalt (Månberger and Stenqvist, 2018), in addition to the co-production of ferromanganese alloy that is used for steels applications. This prospective LCA, based on detailed engineering calculations, envisages three impact categories: climate change, photochemical oxidant formation and acidification (terrestrial and freshwater). The target audience for this study are policy-makers, industry players, civil society, LCA community, scientific community, and the general public, including non-governmental organizations.

2. Material and methods

2.1. Goal and scope of the study

The goal of this LCA study is to evaluate the environmental sustainability of mining and refining processes of deep-sea nodules, considering the value chain from cradle-to-gate (or "from nodules-to-metal commodities"). Moreover, the results are intended to be compared to terrestrial mining benchmarks, with equivalent system boundaries. As the deep-sea mining and mineral processing system is not yet in operation, the LCA study is considered as a prospective LCA. An LCA is prospective when the emerging technology studied is in an early phase of development (e.g., small-scale production), but the technology is modelled at a future, more-developed phase (e.g., large-scale production) (Arvidsson et al., 2018).

2.1.1. Description of the foreground system (deep-sea-sourced commodities)

The scope of the Life Cycle Assessment (LCA) study for deep-sea mining and refining refers to a cradle-to-gate approach, or from nodule-to-metal commodities. The product system can be divided in two main systems: offshore and onshore. The offshore system is subdivided in five modules ("off-modules"), while the onshore is subdivided in four modules ("on-modules"), as described below and in Fig. 1.

In off-module 1 (nodule harvesting), the nodule collectors harvest a mixture of water, sediments and nodules and, after sizing and separation operations, exhaust a "primary mix" (nodules/sediment/water) to off-module 2 (vertical transport system) and another exhaust of "secondary mix" (nodules/sediment/water) goes to the seabed. In off-module 2 (vertical transport system), the "primary mix" is vertically transported to the mining vessel, via centrifugation or positive displacement pumps. In the mining vessel, at off-module 3 (pre-processing on mining vessel), this flow goes through a rotary screen, hydrocyclones and dewatering, generating an output called "nodules mix", which will proceed to storage and an output called "quaternary mix" is returned to the seabed/ water column. Once the storage capacity is reached with the nodules mix, it is transferred to the Bulk Carrier, at off-module 4 (transshipment) by conveyor belt. Finally, at off-module 5 (shipment onshore), the "nodules mix" is shipped to a harbor for further processing. The overall energy source for these offshore operations is maritime fuel (e.g., heavy fuel oil (HFO)).

The onshore operations start with a transportation from the harbor to the onshore operations site, assumed to be performed by train (with 10 km of distance) (on-module 1). Then, at on-module 2 the comminution process happens, i.e., the nodules mix goes through milling and classification. After that, there is a combination of metallurgical processing (on-module 3) via SO_2-processing technology. Furthermore, the last step consists of three parallel activities: high-carbon ferromanganese smelting, copper sulfide refining and mixed sulfide product refining, in order to obtain four final commodities, i.e., ferromanganese, copper (metal), nickel (metal) and cobalt (metal) (on-module 4). Considering that this LCA study is prospective, it is important to clarify the technology readiness level (TRL) of each module, which is available in the Supplementary Material (Appendix A).

The SO_2 process (on-module 3) is a relevant one in the onshore activities, due to the innovations behind it, i.e., a patent was recently published (Daniels, 2021) and its material and energy intensity. Its flow-sheet is presented in Fig. 2. The process is suitable for the recovery of copper, nickel, cobalt and manganese. The polymetallic nodules are processed by a single-step leaching using SO_2 and sulfuric acid. Copper can be recovered from the Pregnant Leach Solution by precipitation as a sulfide. In a subsequent step, cobalt and nickel can also be precipitated as a mixed sulfide product. Finally, manganese is crystallized as a sulphate and then thermally decomposed to a manganese-iron oxide. The mother liquor is split in two fractions, the first being recirculated directly to the leaching stage, and the second seeing the residual iron and manganese precipitated as carbonates or hydroxides, which can be used as acid-consuming compounds in the steps of neutralization. The second fraction of the mother liquor is then processed through reverse osmosis, the process water being recirculated to the leaching stage and the final bleed stream providing an output to minor elements.

The function of the system is the delivery (to the market) of four commodities (Copper, Nickel, Cobalt, and Ferromanganese). Therefore, as this is a multi-output product system, the LCA study is characterized as a *Basket of Products* approach (or System Expansion), composed of four products that are marketable, starting from one tonne of (dry) nodules. In order to quantify the amount of products, as a reference value, the Functional Unit (FU) is defined. To establish that, the reference flow (RF) considered in this study was one tonne of dry nodules. This RF generates the amount of 10.5 kg of copper, 12.8 kg of nickel, 2.3 kg of cobalt and 311.3 kg of ferromanganese, and these four quantities compose the FU of this process-oriented LCA study (Schrijvers et al., 2020a,b).

Two scenarios were considered, A and B. Their differences rely mainly on the location of the onshore operations, which affects (i) the distance to be travelled (in module off – module 5) and (ii) the electricity mix in all onshore processes. For the former, the distances between the polymetallic nodules site and the harbor at the respective countries at scenario A and B are 4,010 km and 2,000 km, respectively. For the latter, the electricity mix in scenario A is composed of hydropower (85%), natural gas (6%), coal and lignite (4%), wind (2%), amongst others (3%); while for scenario B, it is mainly composed of natural gas (55%), hydropower (15%), coal and lignite (13%), oil (10%), nuclear (4%), amongst others (3%). Scenario A considers a country located at about twofold longer distance from the polymetallic nodules site, but with a more renewables-based electric mix than scenario B. The scenarios A and B refer to real countries with actual distances and power mix, but the explicit names of these countries are omitted for confidentiality reasons (which does not affect the interpretation of the results).

2.1.2. Description of the comparative terrestrial mining system

Many different data flows from several terrestrial mining systems were required to make a representative comparison with deep-sea mining system (e.g. electricity consumption at different stages, consumption of chemicals in metallurgical processes, etc.). Therefore, it required access to publicly available data in life cycle format. The main source of data with that format are normally life cycle inventory databases (e.g. Ecoinvent and Gabi), but recently metal commodity associations have been releasing more up-to-date datasets. Therefore, for this study, generic data provided by the metal commodity associations were used, for Copper, Nickel and Cobalt. For Ferromanganese, as no datasets were found from the respective commodity association, a dataset from Gabi database was used. All the datasets (from the commodity associations and from Gabi Database) were obtained from Gabi Software (v8.7 - database SP 37).[1] They were exported in international life cycle data system (ILCD) format, converted to comma-separated values (CSV) format, and then imported in Simapro software v9.0 (where the deep-sea system was modelled), in order to complete the LCA study. In all cases, they were used without any modification or adjustments, e.g., the energy mixes were as provided by their sources.

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[1] The name of the datasets in Gabi Database were: (i) Copper cathode (>99.99%), (ii) Nickel (Class 1, 99.95%), (iii) Cobalt, refined (metal); hydro- and pyrometallurgical processes; production mix, at plant; >99%Co, and (iv) Ferro-manganese, refined (Ref. FeMn), 80 to 85 wt % Mn, less than 1.5 wt % carbon.

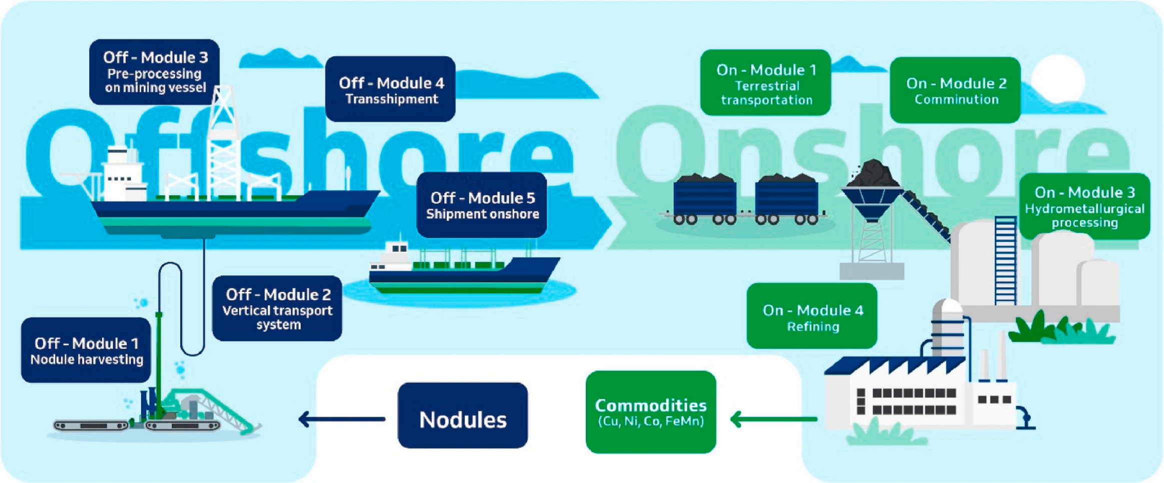

Fig. 1. Simplified flowchart of the product system and its system boundaries (illustrated by the shaded area).

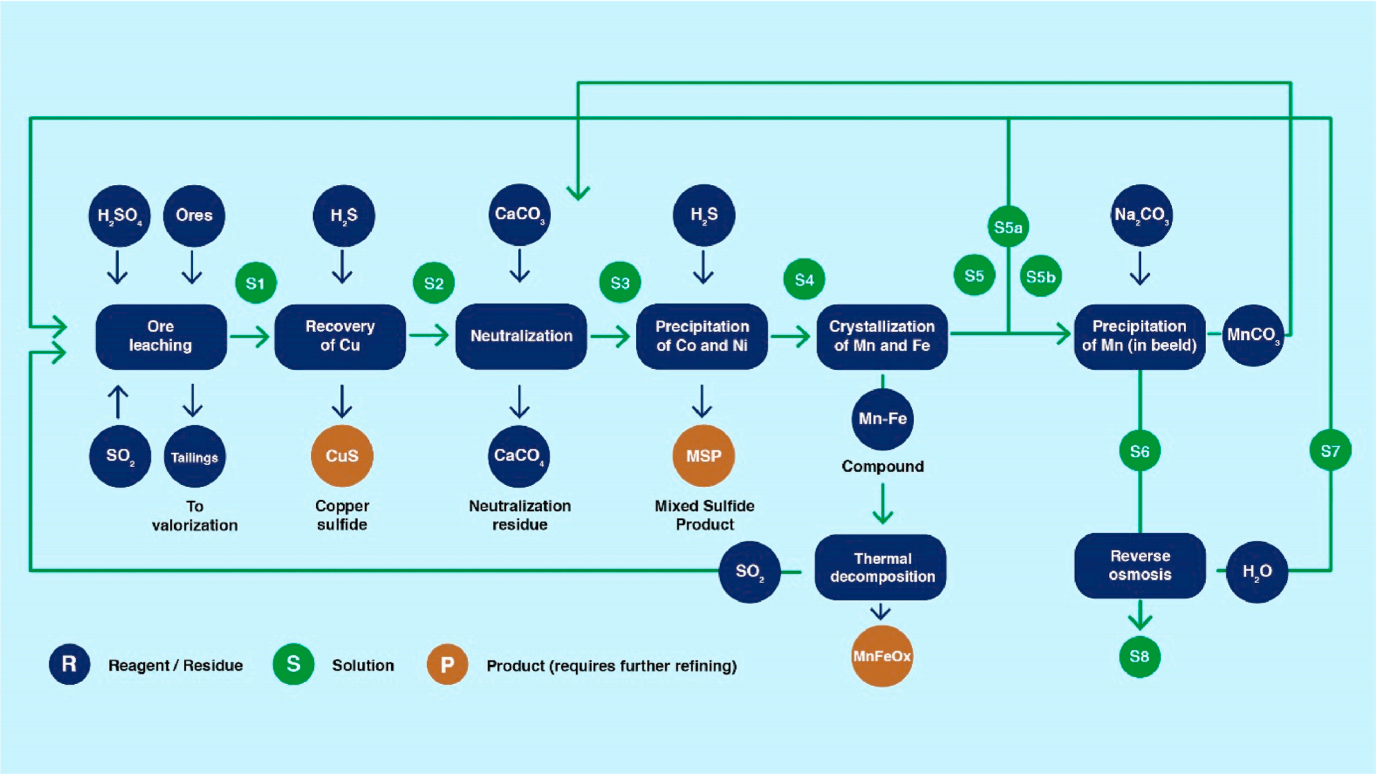

Fig. 2. Simplified flowchart of the SO_2 process. The reagent, residues and products streams are detailed in the figure. The solution streams are as follows. **S1**: PLS (pregnant leach solution), **S2**: Cu-depleted PLS, **S3**: neutralized Cu-depleted PLS, **S4**: Cu, Ni, Co-depleted PLS, **S5**: mother liquor containing a minor part of the Mn and Fe, **S5a**: recirculated mother liquor, **S5b**: bleed stream, **S6**: depleted salt solution, **S7**: essentially H_2O, **S8**: final bleed stream, essentially a concentrated salt solution (the main products – MSP, MnFeOx, CuS – still require further refining).

For Copper, the dataset used refers to a global average production from 2013, covering 21% of World production (developed by the Copper Alliance). For Nickel, it is also a global average production, but for the year 2011, and covers 40% of World production (developed by the Nickel Institute). For Cobalt, the global average dataset refers to the year 2012, covering 30% of World production (developed by the Cobalt institute). Furthermore, for ferromanganese, the dataset used (from Gabi database) refers to operations in South Africa. The details of world coverage and time frame of the dataset are unclear, but according to USGS (2020) South Africa is the biggest producing country, with approximately 30% of worldwide production. Overall, those datasets were considered to be the best publicly available for those four commodities and were therefore used for comparison.

It is arguable that the ferromanganese market would be growing fast enough to accommodate the production considered in the current work, and it is possible that the high-carbon ferromanganese resulting from this process would displace a production that is based on a lower quality carbonate ore, which is known to evolve an additional quantity of CO_2 during the smelting process. However, from an environmental standpoint, considering an addition rather than substitution is a conservative assumption that has been used for this study, and therefore the displacement of a more CO_2-intensive product has not been considered.

2.1.3. Other relevant items regarding the scope of the LCA study

The LCA was performed mainly through a *basket of products* approach, thus, allocation amongst the four commodities (Cu, Ni, Co, FeMn) was not necessary. Moreover, in the case of energy surplus, the substitution (or *avoided burden*) approach was used following the typical procedure from the mining sector and the recommendation from Santero and Hendry (2016). This substitution approach consists of subtracting the burdens from an alternative technology to generate this energy. The country-specific electricity grid mix was considered in this case. In the case of by-products with low market value, e.g. Gypsum ($CaSO_4$), no allocation was performed; it was considered as burden-free.

Data for the foreground system (deep-sea mining commodities), both onshore and offshore, are based on calculations, considering engineering requirements (e.g., energy use), directly provided by the team of experts from the organization involved in this future operation. The calculations are based on the technology specific for the prospective system, taking into account the respective temporal scope. Emissions from fuel combustion and reactions on refining/smelting stages are based on stoichiometric calculations and/or models from secondary sources (Ecoinvent, 2019). More clarification on the foreground system's data calculations is available in the Supplementary Material (Appendix B). For background data, e.g. energy supply chains, Ecoinvent database v3.5 (Ecoinvent, 2019) was used. Most of the flows were modelled considering specific datasets in Ecoinvent (2019), e.g. country-specific electricity mix, HFO and its emissions on ships, etc. On the other hand, a few flows may be generic without temporal, geographical, or technological specification due to lack of availability in the database.

This study attempted to follow the recommendations from Santero and Hendry (2016) regarding the choice of environmental impact categories. However, Eutrophication and Ozone Depletion were not considered in this study because crucial flows for those categories are not properly and consistently documented in the utilized databases (ecoinvent and Gabi), eventually leading to biased results. Therefore, the study is focused on three environmental impact categories, i.e., climate change, photochemical oxidant formation and acidification. The employed life cycle impact assessment (LCIA) models are those recommended for the EU's product environmental footprint (PEF) (Fazio et al., 2018): (i) IPCC 2013, for a time horizon of 100 years, with some adaptations (as described in Fazio et al., 2018); (ii) LOTUS-EUROS, as applied in the ReCiPe2008; and (iii) Accumulated Exceedance; respectively.

3. Results and discussion

3.1. Life cycle inventory of deep-sea-sourced commodities

The life cycle inventory (LCI) of the deep-sea-sourced commodities is available in Table 1. All flows are in function of one tonne of nodules (dry content). Due to confidentiality, the LCI is aggregated in the two main processes, i.e., offshore and onshore. The emissions from fuel combustion are not explicitly reported in Table 1, but they were modelled (and therefore accounted in the LCA study) considering the most representative dataset from ecoinvent database v3.5 (e.g., Heat, district or industrial, other than natural gas {RoW}| heat and power co-generation, hard coal). Therefore, the emissions of carbon monoxide (CO) and carbon dioxide (CO_2) reported at the onshore process (FeMn smelting) are referring specifically to the emissions from the consumption of coke and electrodes (carbon) (Table 1).

The elementary flow to deliver one tonne of dry nodules is apparently high at 63 tonne of water sediment and nodules mix, but this is inherent to a hydrodynamic nodules collection system. Approximately 90% of this mix is actually returned from the collector to the seabed at

Table 1
Life Cycle Inventory of four commodities obtained from deep-sea mining (all flows are in function of 1 tonne of dry nodules).

Stage	Flow type	Flow name	Amount	Unit	Comments
Offshore	Input	Water-sediment-nodules mix	63.0	tonne	
Offshore (A)	Input	Heavy fuel oil, transport[a]	469.2	kWh	Offshore operations and offshore transportation (to country A)
Offshore (B)	Input	Heavy fuel oil, transport[a]	355.2	kWh	Offshore operations and offshore transportation (to country B)
Onshore	Input	Transportation, by train	14.3	tonne. km	Onshore transportation, considered to be by train
Onshore (A)	Input	Energy, renewables (A)[b]	935.8	kWh	For electricity, in country A
Onshore (A)	Input	Energy, fossil & nuclear (A)[b]	1,603.6	kWh	For thermal power and electricity, in country A
Onshore (B)	Input	Energy, renewables (B)[b]	195.0	kWh	For electricity, in country B
Onshore (B)	Input	Energy, fossil & nuclear (B)[b]	2,344.4	kWh	For thermal power and electricity, in country B
Onshore	Input	Water onshore, processing	4,521.3	kg	
Onshore	Input	Reagents, SO2-process	148.1	kg	Sulfur, soda ash, dihydrogen sulfide
Onshore	Input	Reagents, HC FeMn smelting	94.4	kg	Metallurgical coke, graphite electrodes
Onshore	Input	Reagents, Refining processes	168.0	kg	Lime, electrodes steel casing, alumina refractory
Onshore	Waste/ By-product	Residues SO2-process	1,239.9	kg	Tailings, neutralization residues, bleed
Onshore	Waste/ By-product	Residues, Refining processes	317.2	kg	Slag (85% slag, 15% water), gypsum
Onshore	Waste/ By-product	Water (to air), HC FeMn smelting	145.0	kg	
Onshore	Waste/ By-product	CO, HC FeMn smelting	88.0	kg	
Onshore	Waste/ By-product	CO_2, HC FeMn smelting	138.0	kg	
Onshore	Waste/ By-product	Wastewater, for treatment[c]	3,820	kg	
Onshore	Product	Ferromanganese	311.3	kg	
Onshore	Product	Copper	10.5	kg	
Onshore	Product	Nickel	12.8	kg	
Onshore	Product	Cobalt	2.3	kg	

[a] The combustion emission from these flows were accounted for through representative datasets from ecoinvent database v3.5. Moreover, the infrastructure of harbor and the ships, equivalent to their respective life-time in function of the reference flow considered in this study, were also accounted for, as proposed in ecoinvent database v3.5.

[b] Direct (combustion) emissions from energy use are not present in this table, but were accounted through ecoinvent database emission factors.

[c] Only the energy requirements of the wastewater treatment were considered as input (no chemicals) and the effluent was considered to be following local legislation requirements.

very low speed conditions, with only 6 tonne of water, nodules and sediment mix per dry tonne of nodule being vertically transported to the mining vessel.

The HFO consumption for offshore operations (on-module 1–4) is very close to the values reported in Ramboll (2016). Meanwhile, the total HFO consumption for offshore operation and transport (on-modules 1–5) considered in this study (Scenario A: 39.1 kg/tonne dry nodules; Scenario B: 29.6 kg/tonne dry nodules; when a heating value of 12 kWh/kg is considered), is in the same order of magnitude as those reported in Heinrich et al. (2020), i.e., between 10 and 140 kg/tonne dry nodules.

3.2. Environmental impact analysis of deep-sea-sourced commodities

As displayed in Fig. 3, the *basket of products* to process 1 tonne of dry nodules generate different results, depending on the location of the onshore operations (scenario A or B). In the country with more renewable-based electricity (scenario A), the environmental performance was 1,371 kg CO_2-eq, 8.7 kg NMVOC-eq and 11.5 mol H^+-eq, for climate change, photochemical oxidant formation and acidification, respectively. Meanwhile, for the country with more fossil-based electricity (scenario B), the environmental performance was 1,832 kg CO_2-eq, 9.5 kg NMVOC-eq and 12.7 mol H^+-eq, for climate change, photochemical oxidant formation and acidification, respectively. Thus, it is clear that for the three categories, scenario A shows better performance than B, with less environmental impacts in the order of 8–25%.

The main hotspots are overall the same for both scenarios. For climate change, offshore operations have a minor contribution to the total result, especially for scenario B. Onshore operations are in fact the main contributors for climate change, i.e., “on-module 3” and “on-module 4” (ferromanganese smelting), mainly driven by the greenhouse gas emissions from the energy requirements (grid electricity and coal-based thermal power). Nevertheless, the supply chain of some chemical inputs, as lime and soda ash, had a secondary role in those environmental impacts as well.

A similar trend can be seen for photochemical oxidant formation, but the contribution of offshore processes is higher. In fact, the environmental impacts at this category were essentially driven by the emissions obtained from the combustion of fossil energy, i.e., either HFO at offshore processes or electricity use and coal-based thermal power. Mainly, the emissions of CO, nitrogen oxides, and sulfur oxides were contributing to the environmental impacts.

Finally, for the acidification category, a higher relevance of offshore processes is observed, but this is highly dependent on the maritime transport distance. In scenario A, located at approximately 4,000 km from the nodules site, the offshore processes were up to 41% of the total environmental impact. For scenario B, located at 2,000 km from the nodules site, the offshore processes were limited to 28% of the total environmental impact. Moreover, the onshore operations were again the main contributors, mainly due to the emissions of nitrogen oxides and sulfur oxides from the combustion of different energy sources (coal-based or in function of the electricity mix).

In summary, the offshore deep-sea mining operations (off-module 1–4) have a rather low contribution to the total impact (for those three categories); while the transportation of these polymetallic nodules onshore (off-module 5) can have more significant contributions, depending on the location of the onshore operations site from the offshore nodules site (especially for the acidification category). Moreover, onshore operations are the main contributors for all three categories and are highly influenced by the energy source. Therefore, more renewables-based energy source (as in Scenario A, for electricity) is a key element to lower the environmental footprint.

This higher contribution of onshore operations is also observed by Paulikas et al. (2020) for climate change impacts. In Heinrich et al. (2020), the estimated climate change impact of the offshore system was in the order of 30–160 kg CO_2-eq/tonne dry nodules. The upper limit is

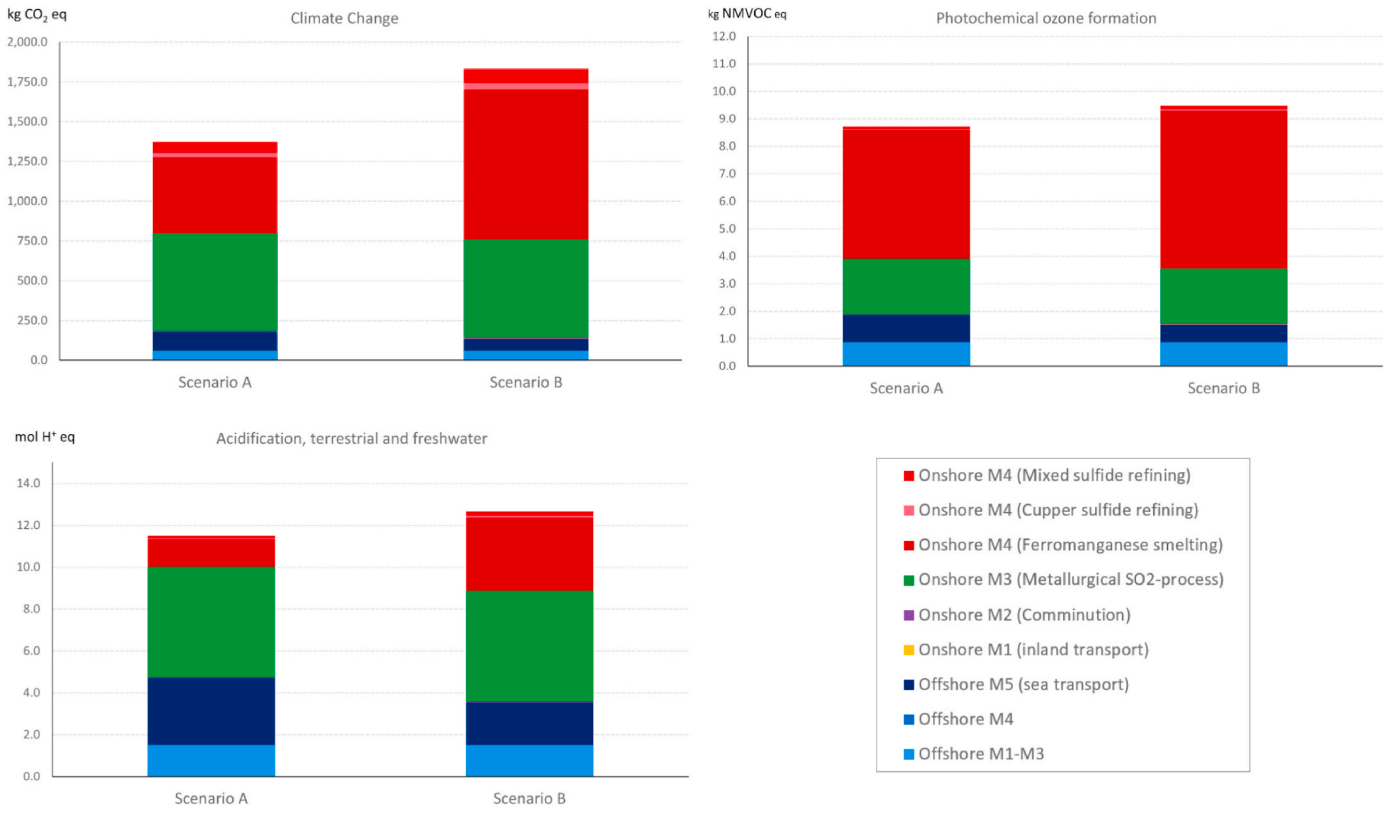

Fig. 3. Environmental performance of the cradle-to-gate processing of copper, cobalt, nickel and ferromanganese from the deep sea (all values are in function of one tonne of dry nodules). Climate Change on top-left, Photochemical oxidant formation on top-right and Acidification on bottom-left.

closer to the results of the offshore contribution presented in this study, i.e., approximately 180 kg CO_2-eq/tonne dry nodules for scenario A and 136 kg CO_2-eq/tonne dry nodules for scenario B (Fig. 3). The reason for higher values in this study can be explained mainly by three aspects. First, there are differences in the scope and system boundaries (e.g., different locations for onshore processing). Second, the use of ecoinvent database (v3.5) in this study, which drives different upstream emissions, e.g., the climate change impacts of HFO (0.49 kg CO_2-eq/kg HFO), is approximately 30% higher than the value considered in Heinrich et al. (2020). The burdens related to the infrastructure for the harbor and the ships (mining vessel and bulk carrier) are accounted for in ecoinvent database (which represented approximately 20% of the offshore climate change impact in this study, whereas Heinrich et al. (2020) only considers effects related to fuel consumption). Finally, slightly different characterization factors were used, i.e., in Fazio et al. (2018) the characterization factors of methane and carbon monoxide are 36.75 and 1.57 kg CO_2-eq/kg, respectively, while in Heinrich et al. (2020) it was considered as 34 and 0, respectively. Moreover, as different LCIA methods (with different units) were used for photochemical oxidant formation and acidification categories in Heinrich et al. (2020), it is not possible to directly compare the results for these impact categories.

3.3. *Comparison of deep-sea-sourced commodities with terrestrial-based*

For the comparison between deep-sea-sourced commodities (Scenarios A and B) and the terrestrially sourced commodities, the results are provided through a *basket of products* approach. This means that all commodities that are produced through processing one tonne of (dry content) nodules are compared with the equivalent amount from terrestrial mining (Fig. 4).

For climate change, the terrestrial products would have a total environmental impact of 2194 kg CO_2-eq, while deep-sea-sourced commodities would have 1371 or 1832 kg CO_2-eq, for scenarios A and B, respectively. Therefore, it is interesting to notice that deep-sea-sourced commodities have the potential to decrease 38 or 16% of the carbon footprint of these products, depending on the scenario, respectively.

For the other categories, different situations are observed. For photochemical oxidant formation, terrestrial products have equivalent/similar results as the two scenarios of deep-sea-sourced commodities. While the terrestrial products had a performance of 8.9 kg NMVOC-eq, scenario A (with 8.7 kg NMVOC-eq) shows a decrease of 2%, while scenario B (with 9.5 NMVOC-eq) shows an increase of 7% on the impacts. For acidification on the other hand, the terrestrial shows always worse performance than the deep-sea-sourced commodities with a total footprint of approximately 42 mol H^+-eq; while deep-sea-sourced commodities would have a performance of 11.5 and 12.7 mol H^+-eq, for scenarios A and B, respectively. This means that the deep-sea-sourced commodities have a potential to decrease the impacts of acidification in a range of approximately 70–72% (depending on the scenario).

One of the reasons for a better environmental performance of the minerals from deep-sea, in comparison to terrestrial sources, can be attributed to the quality of the original material and, consequently, its energy requirements for mineral and metallurgical processing. Duhayon and Boel (unpublished results) state there is an undisputable environmental advantage associated with the comminution of polymetallic nodules as compared to conventional (monometallic) land-based ores, due to their higher grade, polymetallic character and comminution behavior.

While for the deep-sea-sourced commodities it was possible to discriminate the main hotspots (e.g., energy requirements at onshore processing), this is not possible for the terrestrial commodities, since the data are reported in an aggregated format (i.e., not discriminated by

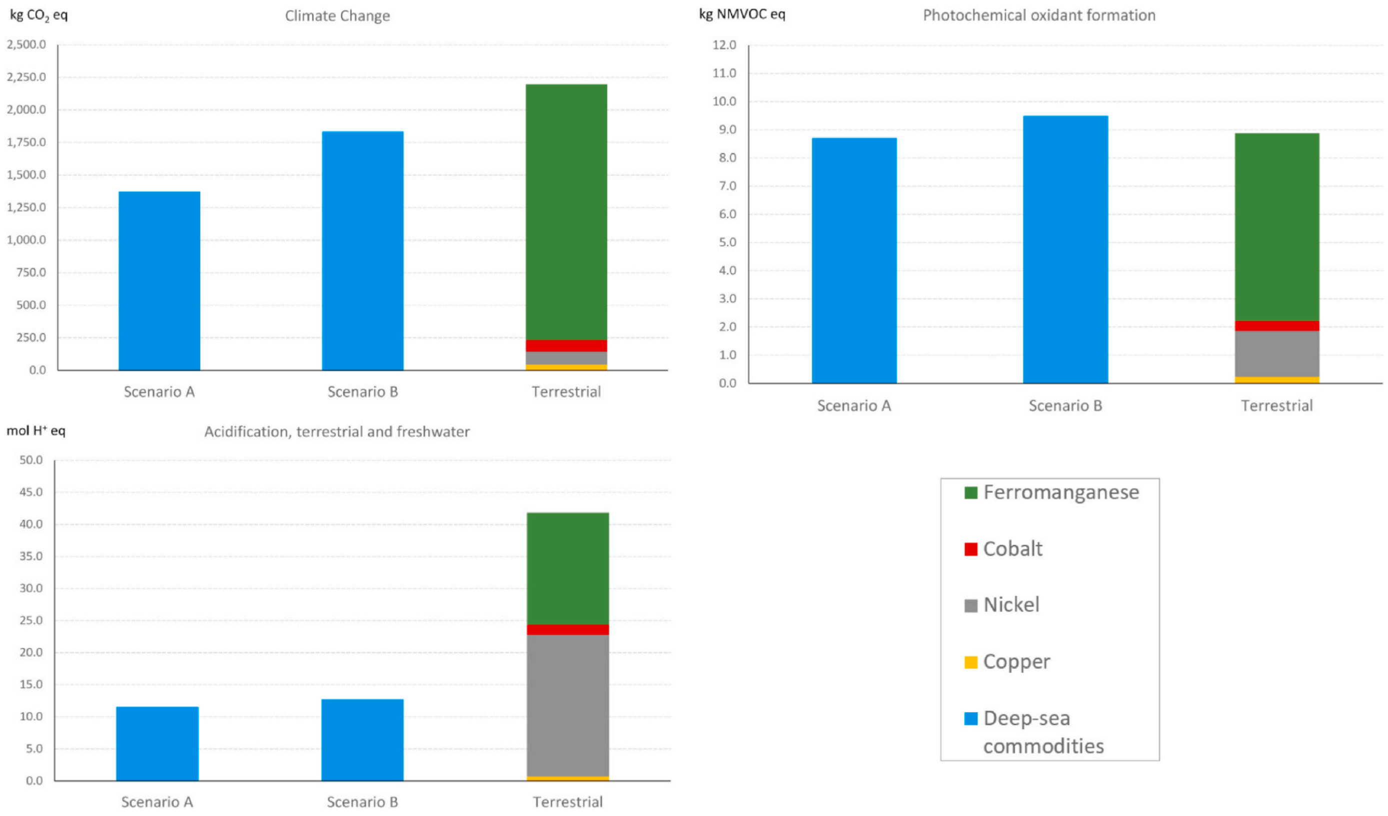

Fig. 4. Comparative environmental performance of the cradle-to-gate processing of copper, cobalt, nickel and ferromanganese from the deep sea and land-based mining system (all values are in function of one tonne of dry nodules). Climate Change on top-left, Photochemical oxidant formation on top-right and Acidification on bottom-left.

different unit processes). However, the contribution of each terrestrially sourced commodity to the entire basket of products is visible. In absolute terms, it is clear that ferromanganese (for climate change and photochemical oxidant formation) and nickel (for acidification) are the commodities that bring most of the environmental impacts in the terrestrially sourced basket of products. Nevertheless, considering the amounts of each commodity in this basket of products (10.5 kg of copper, 12.8 kg of nickel, 2.3 kg of cobalt and 311.3 kg of ferromanganese), cobalt has quite a high relative contribution to climate change, while nickel is the main relative contributor for acidification, and both cobalt and nickel are the main contributors for photochemical oxidant formation. According to Wei et al. (2020), the climate change impacts of four different routes for terrestrial nickel production are mainly caused by the energy requirements of the mining, beneficiation, calcination/sintering, and smelting processes, i.e., electricity and fossil fuels use. Westfall et al. (2016) pointed out that electricity demand and coal and coke consumption during the smelting step are the main contributors to the environmental performance for manganese alloy production. Furthermore, Farjana et al. (2019) performed a review of several LCA studies of metal/mineral commodities, identifying that the energy use (electricity and/or fuel) at different stages (e.g., mining, refining, smelting, etc.) are usually the main contributor to the environmental impacts for copper, cobalt, nickel and ferroalloys (as FeMn); therefore, large variations on the LCA results can be observed due to differences on the material quality (e.g. ore grade), metallurgical processes, sources of fuel and electricity and transportation distances.

Paulikas et al. (2020) also showed better environmental performance on climate change for the deep-sea products, corroborating the results of this study. Notwithstanding, it is important to clarify that the aforementioned LCA study was performed considering different aspects related to scope. First, it was focused on the production of raw materials from deep-sea for electric vehicles, therefore, 95% of the manganese-bearing slag (and the environmental burdens of its downstream processing) were excluded from the study; while this study considered all four raw materials (Cu, Ni, Co and FeMn) regardless their final use downstream. Second, onshore processing electricity demand was assumed to be fully provided by hydropower, while in this study it considered current electric mixes from two different countries. Furthermore, terrestrial mining was modelled for future scenarios considering decrease in ore grades and changes in electric mix, while this study considered current available datasets from reliable sources (e.g., metal associations). Finally, it was focused on climate change, while this study considered also two additional impact categories; among other issues (e.g. functional unit, source of primary data, etc.).

3.4. *Variability of data in terrestrial-based commodities*

The environmental profile of metal commodities from terrestrial mining can be quite different, depending on the source of data (e.g., location of the mine; country where the metallurgical processing occurred). In this study, the most reliable and publicly available datasets were used, mainly coming from the international metal associations (for cobalt, copper and nickel), representing global averages. These datasets provide the information solely in an aggregated format, not allowing to track what potential variability of results could exist, e.g., in the case of data from specific mines or regions would be considered (e.g., World average copper *vs* copper from Australia *vs* Copper from Chile). When analyzing different sources of primary metals, Norgate et al. (2007) presented a variability of approximately 30 and 17% on carbon footprint of copper and nickel commodities from terrestrial mining, respectively. Dong et al. (2020) showed for copper a variability of 11% in the carbon footprint, while for acidification and photochemical oxidant formation the variability was up to 45 and 63%, respectively. Furthermore, Haque and Norgate (2013) presented a variability of 42% in the carbon footprint of FeMn from terrestrial mining. Therefore, these studies corroborate the hypothesis that there may be relevant variability in terrestrial mining, that might drive differences in the results than those presented in this study for terrestrial mining commodities. Furthermore, whereas the metal associations strive for a global coverage as high as possible to ensure representativeness, there may be still important geographical production zones underrepresented as e.g. China is not included, amongst others.

Moreover, this study is a prospective LCA, and the deep-sea system is not yet operational. Therefore, the provision of deep-sea-sourced commodities in the future would directly compete with new supplies (marginal data), e.g., opening new mines or mining operation at lower ore grade (at current mines). However, the comparative study was not done with this marginal provision of commodities due to lack of available data, but with (global) average values based on current production. Van der Voet et al. (2019) estimated the implications of future demand for metals, considering physical constraints (e.g., higher ore grades), estimating a potential increase of 17 and 22% on the carbon footprint of copper and nickel from primary terrestrial mining, respectively, for environmental profiles between 2010 and 2050 (e.g., Nickel 2010: 22 $kgCO_2$-eq/kg; Nickel 2050: 28 $kgCO_2$-eq/kg). Furthermore, prospective LCA does not capture further process improvements via learning effects (Thomassen et al., 2020), which may be quite relevant for offshore processes and some onshore process (e.g., on-module 3), as they are at a relatively early stage of development. Hence, as the benchmarking of the performance of deep-sea mining at the beginning of its development is done with terrestrial mining being at full maturity, it should be concluded that the gains of e.g. 38% on climate change impacts in scenario A is rather a conservative estimate of certain environmental benefits of deep-sea-sourced commodities.

4. Conclusions

A cradle-to-gate (or nodules-to-commodity) prospective LCA study of deep-sea mining, considering two scenarios (varying onshore distance and electric mix), was performed and compared to terrestrial commodities. It was observed that onshore processes (e.g., metallurgical processing) represent the most impacting stages in the value chain of deep-sea-sourced commodities, for all three categories considered. Overall, emissions from energy sources (coal-based thermal power and electricity use) were the main hotspots. The offshore activities, while still having its own environmental burdens, had minor contribution, especially for climate change and photochemical oxidant formation. Of course, this statement is limited to those environmental impact categories considered in this study and may differ for other categories, e.g., biodiversity loss from land (or deep-sea) transformation and occupation. Overall, for the three categories, scenario A showed better performance than B, with lower environmental impacts in the order of 8–25%.

When comparing to land-based commodities, the deep-sea-sourced commodities have the potential to reduce the environmental footprint up to 38% for climate change and 72% for acidification (when considering scenario A). However, for photochemical oxidant formation, the environmental burdens are rather similar for both scenarios, but could lead to an increase of up to 7% in scenario B. Therefore, as previously mentioned, it is clear that selecting a clean energy supply for onshore processing can be key when seeking a good environmental performance, either by placing the onshore processes at a country/region with high renewable-based electric grid (as in scenario A), or even considering to directly purchase fully renewable electricity (through green procurement). The latter could impose even better results than those presented in scenario A of this study (in case the same is not done in land-based commodities systems).

This study presents some limitations, as typically happens in prospective LCA; and, therefore, the results should be analyzed with care. For instance, background data (from ecoinvent) to model the supply chain of deep-sea-sourced commodities was based on current (or older) technologies (not future technologies, when deep-sea mining would be operational). Furthermore, data for terrestrial mining can be quite debatable and may impose an additional uncertainty in these results. As the current study was limited to three admittedly important impact categories, other environmental issues may be subject of further research in function of the debate on deep-sea-sourced versus terrestrially sourced commodities (e.g., impacts from land or deep-sea transformation/occupation). Finally, as it is a prospective LCA based on calculations and modelling, more robust foreground LCI data may become available in the future when reaching piloting or industrial phases of the project. In fact, this foreground LCI data based on higher technology-readiness-level systems can actually result in lower water and energy consumptions (leading to lower environmental footprint), as typically seen in technological learning curves (Thomassen et al., 2020); or even in finding alternative solutions to flows currently handled as residues, as the gypsum (e.g., using them as mineral additives for cement industry).

Nevertheless, the results showed the potential environmental gains that deep-sea-sourced commodities can bring to society, as an alternative source of metals in the future for three specific and important impact categories. One relevant advantage is driven by the possibility to choose the location where the onshore processes will occur, that can be important not only to the environmental performance, but also to other sustainability issues, such as social responsibility.

CRediT authorship contribution statement

R.A.F. Alvarenga: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **N. Préat:** Writing – original draft. **C. Duhayon:** Methodology, Validation, Investigation, Resources, Writing – review & editing. **J. Dewulf:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research is a product of independent inquiry that was funded by Global Sea Mineral Resources, Oostende, Belgium, which is carrying out exploration and development work of deep-sea polymetallic nodules in the CCZ. Chris Duhayon is Metallurgical R&D Manager at Global Sea Mineral Resources.

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Appendix A. Supplementary data

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