THE RUSH FOR METALS IN THE DEEP SEA

CONSIDERATIONS ON DEEP-SEA MINING

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Study for Greenpeace e.V., Freiburg, Feb. 2023

Authors
Andreas Manhart
Oeko-Institut e.V.

Ashleigh McLennan
Oeko-Institut e.V.

Ökoinstitut e.V.
Merzhauser Straße 173
79100 Freiburg
Phone +49 761 45295-0
info@oeko.de
www.oeko.de

Greenpeace e.V. (Publisher)
Hongkongstraße 10
20457 Hamburg

V.i.S.d.P.
Till Seidensticker

Press Desk
Phone +49 40 3 06 18-340
presse@greenpeace.de
www.greenpeace.de

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Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

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Authors

Andreas Manhart
Oeko-Institut

Ashleigh McLennan
Oeko-Institut

Contact
info@oeko.de
www.oeko.de

Head Office Freiburg
P. O. Box 17 71
79017 Freiburg

Street address
Merzhauser Straße 173
79100 Freiburg
Phone +49 761 45295-0

Office Berlin
Borkumstraße 2
13189 Berlin
Phone +49 30 405085-0

Office Darmstadt
Rheinstraße 95
64295 Darmstadt
Phone +49 6151 8191-0

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List of Abbreviations

BMS	Battery Management System
CCZ	Clarion-Clipperton Zone
EU	European Union
EV	Electric Vehicle
ISA	International Seabed Authority
LCO	Lithium-cobalt-oxide
LFP	Lithium-iron-phosphate
REO	Rare Earth Oxides
SDG	Sustainable Development Goal
UNCLOS	United Nations Convention on the Law of the Sea

1 Background and introduction

Economic development, population growth and attempts to decarbonise economies by replacing fossil-fuel based technologies with green alternatives such as solar and wind stimulate significant demand growth for a number of commodities, including cobalt, lithium, niobium, tantalum and rare earth elements (Dolega et al. 2021). World market prices for almost all mineral raw materials increased in the years prior to spring 2022 and prices for metals such as cobalt more than doubled from below 30,000 US$/t in early 2021 to around 80,000 US$/t in spring 2022 (DERA 2022). While price hikes of raw materials have been experienced many times before and are often attributed to temporary supply shortages, some scholars argue that minerals and metals required for green technologies will be subject to a lasting demand growth, comparable to the decade-long rush for oil and gas (Paris and Atacama 2022; Blondel and Kleijn 2022). Moreover, recent developments related to the Covid-19 pandemic and the Ukraine war undermined trust in global supply chain relationships and brought back the fear of politically induced supply shortages. Subsequently, raw material policies are about to be readjusted, most likely leading an intensified scramble for raw materials with a particular focus on metals needed for green technologies.

Currently, mining of mineral commodities is almost exclusively conducted on land with only a few activities in shallow waters and within the territorial influence of countries[1]. Nevertheless, deposits in the deep-sea are increasingly moving into the focus of mining companies and raw material analysts.

These deposits are mostly located outside the 200-miles zone[2] in international waters, where no single country holds any sovereign right for mining and exploitation. According to the United Nations Convention on the Law of the Sea (UNCLOS), mining activities are regulated through the International Seabed Authority (ISA), which is located in Kingston, Jamaica, and mandated “to organize, regulate and control all mineral-related activities in the international seabed area for the benefit of mankind […] and to ensure the effective protection of the marine environment from harmful effects that may arise from deep-seabed related activities” (ISA 2022). The ISA has so far entered into 31 exploration contracts for three different deposit types; 7 for polymetallic sulphides, 5 for cobalt-rich ferromanganese and 19 for polymetallic nodules (ISA 2022). The concessions are granted for 15 years and allow the concessionaires to explore the resource potential, but also require them to carry out environmental investigations. So far, no commercial mining activity has been approved by the ISA.

Amongst all deep-sea mineral deposits, polymetallic nodules clearly stick out in terms of resource potential and economic interests. Polymetallic nodules have roughly the size and shape of potatoes and were formed through precipitation of metals around a nucleus. Subsequently, they contain manganese, nickel, copper, lithium, molybdenum, rare earth elements and other metals (Kuhn et al. 2018). But next to their metal contents, their form of occurrence makes them an attractive deposit for mining. The nodules lie on the seabed surface, or within the first 10 cm of sediment cover. Thus, their extraction would not require any breaking of rock, or removals of substantial depths of sediments. In conditions of several thousands of meters water depth, this relative accessibility matters a lot and makes polymetallic nodules by far the most attractive mineral deposit to those interested in mining in the deep-sea.

Polymetallic nodules are found in all large oceans. But in terms of resource potential, the so-called *Clarion-Clipperton Zone* in the central equatorial Pacific attracts most attention. The area covers

[1] Mining in shallow sea is, for example, conducted for tin ores around the Indonesian Bangka Island.
[2] 200 nautical miles (370 km) from the nearest shore.

about 4 million square kilometres and is the world's largest known deposit of these nodules. Out of the 19 exploration concessions granted for polymetallic nodules, 17 are located in this area (ISA 2022). In terms of economic projections, various models suggest that mining of polymetallic nodules may be viable, presupposing economies of scale (≥ 2 million tonnes of nodules per year) and high world market prices for metals. To realize such projects, investment costs of around 1.9 billion US$ are assumed, with additional annual operational costs of 0.5 billion US$ over 20 years (Sharma 2018). While no exploitation contracts have been issued so far, the ISA published Draft Exploitation Regulations in 2019 (ISA 2019).

In June 2021 the government of Nauru asked the ISA to complete regulations to govern deep-sea mining, which – according to ISA rules – must be accomplished within a 2-year timeframe. Nauru is the sponsoring country for Nauru Ocean Resources Inc., which holds an exploration contract with ISA over 74,830 km^2 in the CCZ. According to ISA rules, the request by Nauru must be fulfilled within two years, otherwise Nauru and its partner are entiled to request a licence under the rules in place until then (Lyons 2021). Nauru Ocean Resources Inc. is a subsidiary of the Canadian company "the metals company", which holds similar arrangements with the governments of Tonga and Kiribati, covering a combined exploration area of 224,533 km^2 in the CCZ. While *the metals company* is still quite a small enterprise employing only 31 staff, it has agreements with large multinational companies, including Maersk and Glencore (the metals company 2022).

Considering the growing demand for raw materials, the preparations by private companies, as well as the new fears of politically induced raw material scarcities, deep-sea mining is becoming a more and more plausible scenario. In particular *the metals company* plans to start commercial exploitation in 2024 with the aim of reaching 12.5 Mt/a of wet nodules (the metals company 2022). Nevertheless, decisions on exploitation and precautionary environmental measures for the deep-sea mining are taken by the international community, notably the 168 UNCLOS parties.

This report aims at supporting related decision-making by highlighting selected aspects around raw material supply and deep-sea mining. It does not have the ambition to provide a holistic assessment of all environmental, economic, social and technical aspects, but rather focuses on topics and perspectives that have so far been underrepresented in the debate around deep-sea mining.

2 Resource potentials

Chemical composition of polymetallic nodules and extrapolation of their abundance in the CCZ suggest that these deposits host resource volumes partly exceeding the proven reserves on land. According to data from (Kuhn et al. 2018), this applies to manganese, nickel, molybdenum, cobalt, yttrium, tellurium and thallium with various additional metals such as vanadium, lithium, tungsten and bismuth reaching values in the same order of magnitude as land-based reserves. Such numbers explain the high interest in these deposits as the CCZ. Nevertheless, it must be stressed that such figures are always somehow hypothetical in nature, which goes back to the definitions of the terms '*resources'* and '*reserves*'. According to (ICMM 2019), they are defined as follows:

*"A **Mineral Resource** is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction […]"*

*"A **Mineral Reserve** is the economically mineable part of a Measured and/or Indicated Mineral Resource […]"*

This means that the term resources include deposits that contain relevant metal concentrations, but which may only become attractive for mining when extraction technologies improve and/or commodity prices are sufficiently high to stimulate investments in mining. In addition, resources do not take into account that some areas might be difficult to mine (e.g., because of rough underground terrain), might have an unproportionally low density of nodules, or are located where mining remains legally prohibited[3].

The figures also do not consider the fact that not all metals can be extracted from mined nodules. As with any ore, metallurgic extraction processes of mined material focus on a selection of elements, usually those present in high concentrations and with sufficient economic value. For polymetallic nodules, extraction will primarily focus on copper, nickel, cobalt and manganese (Sen 2018; Zhao et al. 2020) and possibly molybdenum (Sommerfeld et al. 2018) with many other elements reporting to slags, sludges or other by-products of applied processes. Whether they can be recovered from these by-products largely depends on their concentration and associated recovery costs. Many trace elements are likely to be too diluted for recovery. Lithium, for example has average concentrations of 0.0131% in polymetallic nodules of the CCZ (Kuhn et al. 2018), which is significantly lower than lithium concentrations in terrestrial lithium-mines that commonly range between 0.48% and 1.09%[4] (Mining Technology 2021).

It must also be considered that extraction process in the metallurgical processing stage are somehow imperfect. According to available literature, extraction efficiencies for polymetallic nodules may range between over 90% to 100% for copper, cobalt, molybdenum, nickel and manganese (Sommerfeld et al. 2018). *The metals company* reports that its own projected recovery rates at 94.6% for nickel, 86.2% for copper, 77.2% for cobalt and 98.9% for manganese (the metals company 2022).

Thus, reserves are usually the more concrete figures as they indicate the amounts of commodities that can be mined and extracted under currently given technical, economic and legal conditions. And here, it is noteworthy that – under current conditions – no deep-sea deposit can be mined, which is not only due to lacking exploitation concessions, but also extraction technologies that have not yet been tested beyond small-scale pilot projects.

To estimate realistic raw material volumes that may be mined in the deep-sea, it is more appropriate to use models of how mining and mineral processing could realistically look. Such modelling was done by (Kuhn et al. 2018) and (the metals company 2022) and both come to quite similar results indicated in Table 2-1. The table shows that deep-sea mining projects can only supply some metals, of which only cobalt, manganese and nickel might gain relevant world market shares. The extraction of lithium and rare earth oxide (incl. neodymium) are indicated in the data by (Kuhn et al. 2018), but are subject to considerable uncertainties as concentrations are low (see above) and smelting and refining technologies focused on other raw materials, where lithium and rare earth elements are typically reporting to by-products (slags) in low concentrations unfavourable for further recovery.

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3 Various areas of the Pacific Clarion-Clipperton Zone are marked as “Areas of Particular Environmental Interest” by the International Seabed Authority (ISA 2022). No exploration licence is granted for these areas, so that active mining in these areas is highly unlikely in the decades to come.

4 Equivalent to 1.04% and 2.35% Li_2O.

Table 2-1: Comparison of annual metal production with potential outputs of deep-sea mining in the Clarion-Clipperton Zone

	production 2021	Estimated production of 5 nodule mining projects (total of 10 million t of dry nodules per year)	Estimated full-scale production of 'the metals company' and subsidiaries after 2030 (total of 9.5 million t of dry nodules per year)	Estimated production of 5 nodule mining projects as percent of 2021 production	Estimated production of 'the metals company' and subsidiaries after 2030 as percent of 2021 production
	[1000 t/a]	[1000 t/a]	[1000 t/a]	[%]	[%]
	USGS 2022; Deetman et al. 2018 (for Nd)	Kuhn et al. 2018	the metals company' 2022		
Aluminium	68000	0	0	0%	0%
Chromium	41000	0	0	0%	0%
Cobalt	170	17	10	10%	6%
Copper	21000	118	93	0,6%	0,4%
Graphite	1000	0	0	0%	0%
Indium	0,92	0	0	0%	0%
Iron	1600000	0	0	0%	0%
Lead	4300	0	0	0%	0%
Lithium	100	1,4	0	1%	0%
Manganese	20000	3000	2931	15%	15%
Molybdenum	300	6	0	2%	0%
Neodymium	23000	1,4	0	0,006%	0%
Nickel	2700	139	126	5%	5%
Silver	24	0	0	0%	0%
Titanium	9000	0	0	0%	0%
Vanadium	110	0	0	0%	0%

Used data for column 4
annual collection of wet nodules = 12,5 Mt
water content = 24%
abundance = 17,1 kg/m2 (wet nodules)
Ni-content = 1,4%
Cu-content = 1,14%
Co-content = 0,14%
Mn-content = 31,2%
Ni extraction efficiency = 94,6%
Cu extraction efficiency = 86,2%
Co extraction efficiency = 77,2%
Mn extraction efficiency = 98,9%

Source: Calculated with data from (USGS 2022; Kuhn et al. 2018; the metals company 2022; Deetmaan et al. 2018)

Key takeaways

- Polymetallic nodules – in particularly those of the Clarion-Clipperton Zone – are currently the deep-sea deposit receiving highest interest from a resource-supply perspective, as well as an economic perspective.
- While the indicated resource potentials are very high and partly surpass the land-based reserves, this does not mean that these volumes can realistically be mined. Even after granting exploitation concessions, mining projects can only generate a fraction of these potentials.
- It is also important that many trace metals contained in the nodules will likely not be extracted in metallurgic process. Thus, resource potential for all elements other than copper, cobalt, molybdenum, nickel and manganese must be taken with caution.
- Deep-sea mining projects that may realistically start full-scale operation no sooner than 2030 might gain relevant world market shares for cobalt, manganese and nickel, but not for other metals.

3 Demand projections

All market analysts anticipate growing demand for raw materials required for green technologies such as energy storage (batteries), wind turbines and photovoltaic modules. Cobalt, graphite and lithium are in the centre of these projections and the World Bank projects that these are the only raw materials where energy technologies might require around 4 and 5 times of the current annual production in 2050 (see Table 3-1) [5].

Table 3-1: 2021 mineral production and projected annual demand from energy technologies in 2050

	production 2021	2050 projected demand from energy technologies	2050 projected demand from energy technologies as percent of 2021 production
	[1000 t/a]	[1000 t/a]	[%]
	USGS 2022	World Bank 2020	
Aluminium	68000	5583	8%
Chromium	41000	366	1%
Cobalt	170	644	379%
Copper	21000	1378	7%
Natural graphite	1000	4590	459%
Indium	0,92	1,73	188%
Iron	1600000	7584	0,5%
Lead	4300	781	18%
Lithium	100	415	415%
Manganese	20000	694	3%
Molybdenum	300	33	11%
Neodymium*	45	8,4	19%
Nickel	2700	2268	84%
Silver	24	15	63%
Titanium	9000	3,44	0,04%
Vanadium	110	138	125%

* Neodymium data based on rare earth oxide production volumes and an average Nd-content of 16% (TMR Research 2022)

Source: (World Bank 2020; USGS 2022)

While there is a wide consensus on a generally growing demand, the estimated 2050 mineral demand for energy technologies (incl. transport) are very sensitive to the climate scenarios they build upon. This includes the scenarios on future overall transport and energy demands, the future shares of different transport and energy solutions within these demands, as well as the assumed technological developments, innovations and other factors. Please refer to the specific underlying scenarios and assumptions behind the numbers in the table to World Bank (2020)."In this context, it

5 We acknowledge that World Bank's demand estimation is only one of the possible available projections built on a particular set of scenarios and assumptions and recently several alternative relevant projections have been published. For this study we use it as an example.

is noteworthy that the World Bank projections presented in Table 3-1 do not account for potential changes in Li-ion battery sub-chemistries but assume that material compositions of Li-ion batteries in 2050 are the same as today. Considering the rapid and ongoing development of this battery technology, this assumption is highly unlikely and sheds light onto common uncertainties related to demand projections over various decades. Subsequently, quantitative projections diverge significantly and range from a global annual demand of 150,000 t to 558,800 t in 2030 for lithium[6] (Schmidt 2022), and similar bandwidths for cobalt (Giurco et al. 2019; Miller et al. 2021). Such uncertainties are particularly pronounced for raw materials that are used in a small range of applications and the World Bank report that published the data of Table 3-1 also states that lithium, graphite and cobalt "are needed only for one or two technologies and therefore possess higher demand uncertainties as technology disruption and deployment could significantly impact their demand." (World Bank 2020). Uncertainties are particularly high for cobalt: while today 57% of the global cobalt production is used for Li-ion batteries (Cobalt Institute 2022), these batteries come in a number of different sub-types, which have different cobalt contents with some requiring no cobalt at all. Shifts in sub-type preferences and chemistries already led to a declining cobalt demand per battery storage capacity and it is expected that this trend will continue (Al Barazi 2018; Betz et al. 2021). According to (avicenne energy 2019), the price for the cathode material (cobalt or substitutes such as nickel) accounts for around one third of the production costs of Li-ion battery cells, which means that price increases for these raw materials will likely stimulate market shifts to battery types with lower or even no cobalt contents, a trend that is already observed in various segments (Willing 2020). Substitution materials such as manganese, nickel, aluminium, iron and phosphate are far less supply critical and increased demand from batteries would only have very limited effects on the world market for these raw materials[7] (see Table 3-1).

[6] Starting from an annual production of 82,000 t in 2020.

[7] In the EU 87% of all manganese and 89% of all nickel are used as alloying elements for different steel products. Only 2% of all manganese is currently used for battery cathodes and 11% of all nickel for electrical and electronic equipment (whereof only a part is used for batteries). The use-share of aluminium in batteries is so low, it is not accounted for in trade statistics (European Commission 2020b). Further data on the global use-share for Li-ion batteries can be found in Figure 4-1.

Key takeaways

- Renewable energies, electric vehicles and other green technologies will stimulate increasing demands for various minerals and metals. The most pronounced demand growths are projected for lithium, cobalt and graphite. The growing demand for these materials almost exclusively comes from a growing demand for Li-ion batteries for electric vehicles and, to a lesser extent, stationary power storage. Nevertheless, there are considerable uncertainties regarding the scale of these demand increases.
- Other raw materials such as copper and molybdenum are likely to experience a much less pronounced demand growth from green energy technologies.
- Polymetallic nodules of the deep-sea contain cobalt and lithium, but no graphite.
- Mining of polymetallic nodules may generate a significant additional cobalt supply. Additional supply for lithium is comparably limited (see Table 2-1). In addition, the feasibility of extracting lithium from polymetallic nodules has not yet been proven and is not targeted by planned deep-sea mining projects (see chapter 2).
- Cobalt demand projections are subject to high uncertainties. While Li-ion batteries are by far the most important driver for increasing cobalt demands, there are various sub-chemistries requiring less or even no cobalt.
- It is plausible that increasing cobalt prices will lead to substitution effects towards other metals such as nickel, manganese, iron and phosphate (which are partly already observed today).
- These substitution metals are produced in large quantities and mainly used in iron and steel production (iron, nickel, manganese) and for aluminium parts and applications (aluminium). Even pronounced demand increases for batteries will have only minor consequences for the world's total demand for most of these materials.

4 Focus on battery raw materials

Electric mobility and the need for Li-ion batteries powering electric vehicles is a central line of argumentation for deep-sea polymetallic nodule mining. The deep-sea mining enterprise *the metals company* uses presentations suggesting that polymetallic nodule mining will alleviate metal supply criticalities for Li-ion battery production and subsequently electric mobility (the metals company 2021). In fact, it appears feasible to extract relevant amounts of copper, manganese, cobalt and nickel from polymetallic nodules (see chapter 3), and it is also correct that these materials are used in Li-ion battery manufacturing. Nevertheless, the presentations by *the metals company* on their website and annual report (the metals company 2021, 2022) widely neglect various other facts around battery raw materials:

- Manufacturing Li-ion batteries needs more types of resources than can be generated from polymetallic nodules. Graphite and lithium are very important battery raw materials too but cannot be generated from polymetallic nodules (also see chapter 3).
- From all Li-ion battery raw materials, only graphite, lithium and copper are really indispensable as they cannot be substituted by other elements without severe consequences[8] (see Figure 4-1). Out

[8] Graphite can be substituted with lithium, but such substitution would only generate shifts towards another indispensable battery raw material.

of these three raw materials, polymetallic nodule mining can only supply copper. But the copper-demand for Li-ion batteries is quite negligible from a world market perspective so that further demand increases from battery production will only have marginal impacts on the global copper market and supply.

- In this regard manganese is very comparable with copper: The requirements for Li-ion batteries are (and will remain) minor compared with other applications. By far the largest share of manganese is used as alloying element for steel.
- Cobalt and nickel are both important cathode materials for various types of Li-ion batteries. But these materials can be substituted with other materials or material-mixes. While such substitutions have influence on battery properties, there are examples of cobalt- and nickel-free Li-ion batteries being applied in the mass market. Amongst others, cobalt- and nickel-free LFP batteries are rapidly gaining market shares in electric mobility in China and are also starting to be used by market pioneers such as Tesla (Willing 2020). Market shares of LFP batteries climbed significantly from around 5% in 2019 to above 30% in 2022 (Wunderlich-Pfeiffer 2022; Kane 2022), replacing many nickel and/or cobalt using battery-chemistries in a comparably short time period.
- Ongoing research in battery chemistries and optimisation will likely open more substitution possibilities in the future. Next to a further optimisation of LFP batteries, the development of Sodium-ion batteries may offer suitable alternatives with pilot production plants operating in China (Wunderlich-Pfeiffer 2022).

Figure 4-1: Overview of Li-ion battery raw materials

	Graphite	3 Li Lithium 6.94	29 Cu Copper 63.546	25 Mn Manganese 54.938	27 Co Cobalt 58.933	28 Ni Nickel 58.693
Can be produced from polymetallic nodules	No	No	Yes	Yes	Yes	Yes
Current share of world supply used for Li-ion batteries	7%	29%	0.01%	0.2%	57%	5%
Substitutable	Yes	No*	No	Yes	Yes	Yes
Substitution materials	Li	-	-	Co, Ni, Al, Fe, P	Ni, Fe, P, Mn	Co, Fe, P, Mn

Graphite, Li, Cu: Indispensable raw materials for Li-ion battery production

Cu, Mn: Raw materials largely used in other sectors

Mn, Co, Ni: Substitutable raw materials for Li-ion battery production

* Substitutable only through shifts to battery types other than Li-ion or Li-metal (e.g. Na-ion batteries)

Source for share of world supply used for Li-ion batteries: Co: (Cobalt Institute 2022) Graphite, Mn, Ni: (DERA 2021); Li: (Ding et al. 2020); Cu: calculated using the following data: total annual Li-ion battery production: 2 million t (assumption based on (Jacoby 2019)); Cu-content of batteries: 12% (DERA 2021), total annual Cu-production: 24 million t (DERA 2021).

Key takeaways

- Presentations by *the metals company* suggest that polymetallic nodule mining is a main means to secure raw materials vital for battery production for electric vehicles. These presentations widely neglect the fact that the two most critical raw materials for Li-ion batteries – lithium and graphite – cannot be produced from the nodules.
- The raw materials that can be produced from polymetallic nodules are partly produced at huge quantities for mass-applications already (copper, manganese). While the Li-ion battery related demand for these raw materials may increase significantly, this additional demand will only have very marginal impacts on the world market of these metals and not induce any supply shortage.
- The other battery raw materials that can be produced from polymetallic nodules (cobalt, nickel) are substitutable through shifts to other Li-ion battery sub-chemistries, which can already be observed today. Although many substitutions will have consequences for battery specifications and properties, ongoing research and development will likely widen the spectrum of substitution possibilities in the future. Considering that deep-sea mining will not be able to supply relevant quantities of raw materials prior to 2030, today's focus on cobalt and nickel might not match future demand realities.

5 Impacts

The mining of polymetallic nodules requires several steps. First, the nodules need to be lifted from the seabed using autonomous mining crawlers which collect the nodules as well as surrounding sediment, 90% of which will be separated and released behind the mining vehicle. From here, nodules will be pumped to the production vessel on the surface via a riser system. The nodules will be separated from the residual water and sediment, which is discharged from the production vessel to below the photic zone (i.e. below 200m). Finally, the nodules will be transported to land for onshore processing (the metals company 2021).

Environmental impacts can occur at each of these steps, with the most direct impacts occurring on the seabed itself (otherwise known as the benthic environment). Due to its inaccessibility and distance from human activities, the deep ocean floor is one of the most intact ecosystems on the planet (Smith et al. 2020), and mining activities would disrupt this ecosystem on several fronts.

Biodiversity impacts (seabed)

There is evidence to suggest that the polymetallic nodules themselves form an important part of the deep-ocean habitat. For example, one study (Vanreusel et al. 2016) found higher densities of both sessile and mobile fauna on or near polymetallic nodules than could be found in nodule-free areas: in nodule rich areas, 14-30 sessile individuals and 4-15 mobile individuals per 100 m^2 were found, while in nodule free areas, only 8 sessile individuals and 1-3 mobile individuals per 100 m^2 were found. One likely reason for this is that the nodules provide shelter and growing surface in an environment otherwise devoid of hard substrates. Certain sponges and molluscs have been discovered which are so far unique to the surface of the nodules, and nematode worms and crustacean larvae have also been found within the crevices of nodules. As only a fraction of the deep-sea has been scientifically studied, more as-yet-undescribed biota may be affected in ways currently unknown (Miller et al. 2018).

A second impact on the benthic environment is the creation of sediment plumes, with the potential to smother deep-sea animals, and/or clog their delicate feeding apparatus (Niner et al. 2018). According to the metals company, over 90% of the sediment collected along with the nodules will be separated inside the collector and discharged behind it, where it will settle within "a few hundred metres" (the metals company 2021). However, the exact behaviour of sediment plumes, including how far they will travel and how long they will remain suspended is not yet understood, as it depends on discharge volume, vertical stratification and ocean currents (Miller et al. 2018). Existing models suggest that it might take sediment plumes up to a year to settle, and that the dispersal could extend tens of kilometres away from the mining site (UNEP FI 2022; Miller et al. 2018).

This wide dispersion has, however, been disputed. For example, (Gillard et al. 2019) state that it is possible to restrict plume fall out to a small area by designing mining collector and exhaust pipes for elevated discharge and turbulence which according to their modelling increases the speed of sediment flocculation. Another study by Spearman et al. (2020) has argued that the focus of modelling studies should be the distance at which the plume concentration becomes small compared to natural background concentration, as opposed to the distance of travel of sediments across the abyssal plain. This hypothesis has been tested in the context of cobalt-rich crusts, but the authors assert that the findings are also relevant to nodule mining (Spearman et al. 2020).

Given the necessary scale of polymetallic nodule mining in terms of area, it is also likely that animals in the benthic environment will be adversely affected by habitat fragmentation. According to Smith et al (2020), the CCZ has been divided into nine ecological subregions, each expected to have different seafloor communities. A substantial portion of three of these subregions are targeted for mining, and the removal of nodules could create extinction risks for nodule dependent biota (Smith et al. 2020). As there have been no large scale trials, the impact on the continuity of habitats is difficult to predict and will depend on the extent of resource extraction as well as associated and potentially far reaching sediment plume dispersal (Miller et al. 2018).

In addition, the noise, heat and light created by the mining vehicles will potentially disrupt animal behaviour. The deep-sea is very quiet, and deep-sea species have evolved sensitive acoustic systems, including communication using low sound frequencies (<1.2 kHz) or the ability to detect food falls up to 100 m away. The persistent, anthropogenic noise caused by seafloor vehicles and hydraulic pumping will substantially increase ambient sound levels and could cause temporary or permanent hearing damage for some species (Miller et al. 2018). Light is also very low in the deep-sea, which the organisms living there have adapted to. Likewise, temperatures in the deep-sea are very stable, and it is unknown what impact heat released by vehicle operation and dewatering waste will have on organisms (Miller et al. 2018).

Another dimension of habitat disruption and/or destruction which should be considered when assessing the impact of deep-sea mining is the slow speed at which the benthic environment recovers. To date, a number of studies have indicated that recovery has not occurred decades after the removal of nodules (Miller et al. 2018). Multiple studies have observed slow recovery rates, including one along the tracks from trawling or experimental mining simulations from 37 years earlier, which found that recolonisation is extremely slow with very little habitation of species decades after the disturbance (Vanreusel et al. 2016). Another study found that there was a 79% difference in respiration rates of suspension and filter feeders between disturbed and non-disturbed areas 26 years after seabed ploughing (Stratmann et al. 2018).

Finally, it is predicted that climate change will further slow this recovery. Over the past 50 years, the ocean below 200 m has already warmed and become more acidic, and these changes are leading to less food supply reaching the deep-seafloor. Rising sea water temperatures will also increase the metabolic rates and energy requirements of deep-sea animals, which will increase food competition/ limitation, as well as increase oxygen requirements. The higher temperatures may even exceed many species' tolerance ranges (Levin et al. 2020).

Ultimately, multiple studies conclude that the true extent of the impact on deep-sea biomass and biodiversity is difficult to predict given the existence of critical knowledge gaps. Basic biological data for most deep-sea animals is missing, including their growth rates, life histories, and tolerance to stressors (both acute and chronic) (Smith et al. 2020) (Washburn et al. 2019). In addition, the connectivity between deep-seabed habitats and the broader ocean ecosystem are poorly understood (Miller et al. 2021).

Carbon sequestration impacts (seabed)

Another uncertainty is the impact that mining activities will have on carbon sequestration on the seabed. Deep-sea organisms play a role in climate regulation through the burial of carbon, and production of oxygen through the recycling of nutrients required by phytoplankton (Niner et al. 2018). Sediments in abyssal/basin zones account for 78% of global marine sediment carbon stocks. Of these, only around 2% are located in highly to fully protected areas, making these carbon stocks vulnerable to the expanding activities on the seabed, including mining (Atwood et al. 2020). When disturbed, the carbon content of deep-sea sediments can become remineralised to CO_2, a process that may exacerbate future climate change (Atwood et al. 2020). However, others estimate that this impact will be small, as deep-sea sediments contain extremely low quantities of highly processed organic matter which is not likely to remineralise, meaning even after disturbance most would be redeposited on the sea floor (Orcutt et al. 2020). As such, it is difficult to conclude whether deep-sea mining will significantly impact global carbon cycling (Levin et al. 2020).

Biodiversity impacts (water column)

Beyond the seabed, other impacts can occur during the transport of nodules to the surface, and then onwards to land. First, after nodules have been transported to the processing vessel at the surface (likely causing noise through the entire water column), the nodules are separated from residual water and sediment, and the tailings are discharged back into the water column, introducing sediment and dissolved metals over large areas. For example, from one polymetallic nodule mining operation, an estimated 50,000 meters-cubed of sediment, mineral fines and seawater will be discharged per day (around 8 kilograms per meter cubed solids). Fine sediments and metals could stay in suspension for several years and be carried for hundreds of kilometres posing risks to the midwater environment (Drazen et al. 2020).

Many suspension feeders (i.e. creatures which filter small particles from the water to feed) live in the midwater zone, forming an important part of the ocean food web. Inorganic sediments released in the water could clog their feeding apparatus, while the discharge of metals and toxins could contaminate and accumulate through the food web. The threshold levels are unknown, however, as deep midwaters have very low concentrations of suspended sediment, it is assumed that animal sensitivities to sediment are likely to be high. Additionally, sediment plumes will negatively impact the opacity of water, interrupting hunting and reproduction behaviours of midwater animals, while noise will also stress and interrupt animal activities. As with the seabed environment, the ecological baselines to assess the true impact of mining activities on midwater environments do not exist (Drazen et al. 2020).

Finally, following initial pre-processing and dewatering on the surface mining vessel, the mined material will likely be transported by ship to the shore. For this stage, all of the normal environmental impacts associated with maritime transport can be expected, including marine pollution, atmospheric emissions, and underwater noise. In addition, accidental spills of mineral ore into surface waters may occur during their transfer from mining vessel to ship (UNEP FI 2022). Once on land, deep-sea minerals are expected to undergo similar processing as terrestrial deposits would, including crushing and chemical extraction of elements. As with other offshore exploration activities, coastal facilities may be constructed to handle this processing, which may result in impacts to the coastal environment (UNEP FI 2022).

Key takeaways

- The mining of polymetallic nodules will disturb the seabed, with negative effects on biodiversity and biomass in the benthic environment. Factors include the removal of the habitat provided by the nodules, as well as the creation of sediment plumes and noise. Habitat fragmentation and slow recovery rates are also critical factors.
- The ocean floor is an important carbon store, and there is a risk that deep-sea mining will negatively impact the carbon sequestration services provided by this ecosystem. Based on current evidence, however, it is difficult to conclude the extent to which global carbon cycling will be impacted.
- The release of mine tailings into the water column may disrupt the food web. Fine sediment may clog the feeding apparatus of suspension feeders, while metal and toxins could bioaccumulate up the food chain. Sediment and noise may also impact the hunting and mating of marine species.
- Mined ores need to be transported by ship to be processed in onshore facilities. Shipping is a source of marine pollution, atmospheric emissions, and underwater noise, and the physical and chemical extraction of minerals from the deep-sea ore can also be expected to have similar impacts to the processing of ores from terrestrial mines.
- The deep-sea remains an understudied environment. Little is known about deep-sea biomass and biodiversity, making the impact of deep-sea mining difficult to predict. In addition, multiple uncertainties exist around the size of the area that would be affected by mining sediment plumes, the impact of mining on the global carbon cycle, and the possible consequences for the ocean food web

6 Summary and aspects of an alternative raw material strategy

As demonstrated in chapter 2 to 4, the mining of deep-sea nodules has a far lower potential for securing raw materials for green energy transition than often portrayed. Polymetallic nodules from the deep-sea may only supply 4 or 5 commodities (manganese, copper, cobalt, nickel, and possibly also molybdenum), of which only 3 could be supplied in volumes relevant for the world market (manganese, cobalt, nickel). The prominent claim that the nodules can secure raw material supply for future lithium-ion battery production is misleading for various reasons:

- The nodules do not provide lithium and graphite, which are the 2 most supply-critical battery raw materials.
- 2 of the entailed raw materials (copper and manganese) are predominantly used for other applications. As Li-Ion batteries account for less than 1% of the world consumption, an increase demand for Li-ion batteries will have almost no impact on the global supply-demand of these materials and will not require a significant expansion of mining activities.

- While cobalt and nickel are extensively used in many of today's Li-Ion batteries, they can both be substituted by other less supply-critical materials. Indeed, the average cobalt content of Li-ion batteries has already been reduced over the last years to limit manufacturing costs, and Li-ion batteries are available on the market which are completely free from cobalt and nickel.
- Research and development will most likely broaden the spectrum of suitable Li-ion battery sub-types and enable more substitution alternatives in the future.

In light of this situation, it can firmly be assured that decisions against deep-sea mining will not cause a halt of global Li-ion battery production and subsequent plans for green energy technologies. Considering the manifold and still incompletely understood potential impacts of deep-sea mining and the vast amounts of seabed surface to be converted for comparably small raw material outputs, it is paramount to apply the precautionary principle and abandon plans for exploitation. Instead, it is recommended to intensify the focus on other strategies for a sustainable supply and use of natural resources. This section aims to shed some light on important corner stones of such strategies that presumably have much higher positive effects on raw material demand and supply.

Rethinking transport patterns

Many forecasts for global battery demand are based on projections for a phase-over from conventional to electrical vehicles. Subsequently they assume that transport patterns based on privately owned passenger cars, including continuous annual growth rates, will continue for the decades to come. But it is widely known to transport and city planners that both numbers and growth rates are unsustainable, not only from a resource demand perspective, but also because of the realities of urban agglomerations. Congestion and hour-long traffic jams are already major factors limiting development potential of cities and nations. The situation is worst in megacities in low- and middle-income countries such as Lagos (Nigeria) or Mexico City where commuters commonly spend several hours in traffic jams per day (Obi 2018; Mexico News 2017). Such traffic situations do not only limit the inhabitants' ability to travel and exchange goods, but also constitute a severe loss of productivity and quality of life. It is therefore time to think beyond replacing conventional vehicles with electric cars of same size and similar designs. The focus should be on finding ways to allow the movement of persons and goods in a more efficient way, consuming less space, emitting less greenhouse gases and not curtailing quality of life and the economic development of people. Considering that more than 55% of the world's population lives in cities (UN-DESA 2018), effective, integrated urban mobility systems are needed more urgently than ever. Realising such integrated urban mobility systems will slow-down the demand for private passenger cars and subsequently electric vehicle batteries.

Develop global take-back and recycling

Li-ion batteries can be recycled at their end-of-life. Although recycling processes are still under development and about to be optimised, it is possible to recover various embedded raw materials at high efficiencies (>95%). This is the case for copper, cobalt and nickel, and there are ongoing attempts to also advance the recovery of lithium and graphite. Development of recycling processes and infrastructure is currently focused on a few Asian, European and N-American countries such as China, S-Korea, Japan, Belgium, Finland, France, Germany and the US (Sojka et al. 2020). Most other countries and world regions do not have their own developed recycling infrastructure for Li-ion batteries, which means that batteries for recycling would need to be shipped to one of the existing facilities located in another country or world region. Here, two major aspects must be considered:

- Shipping of batteries is associated with considerable efforts and costs. This results from the fact that the batteries are widely regarded as hazardous waste, meaning any transboundary movement must follow the prior-informed-consent procedure of the Basel Convention. This process is often associated with considerable administrative burden and potential delays (PREVENT Waste Alliance & StEP 2022). In addition, fire-safety precautions are necessary, and batteries must be embedded in special containers filled with sand, vermiculite or similar, adding to costs and efforts of shipments.

- Applied recycling processes are costly meaning recyclers cannot pay monetary compensation for all types of Li-ion batteries. In recent years, recycling as practiced by European companies only yielded net profits for batteries with high cobalt-contents (LCO-batteries) and suppliers of other Li-ion battery types were charged gate fees (Manhart et al. 2022). High world market prices for raw materials might change this picture temporarily but risks and economic uncertainties are still high.

Subsequently, collection, packaging and export of end-of-life Li-ion batteries are currently not economically attractive in many world regions as sound end-of-life management is commonly associated with net costs (Manhart et al. 2022). Collection and sound end-of-life management (including recycling) can only be effective when supported by national and international policies assigning clear responsibilities and targets for take-back and recycling. In the EU, such targets are set out in the Battery Directive (Directive 2006/66/EC), which is about to be replaced by a more holistic Battery Regulation setting mandatory collection and recycling targets for producers and of batteries. In many parts of Africa, Asia and Latin-America, such systems are either not in place, or not yet fully developed so that battery collection and recycling remain in their infancy. Therefore, the bulk of currently used Li-ion batteries in low- and middle-income countries are not collected and recycled. Instead, batteries are commonly disposed together with other municipal solid waste adding to pollution problems and fire risks.

There are 6.74 billion mobile phones in use in low- and middle-income countries (World Bank 2022). Assuming an average lifetime of 2 years, use of LCO-batteries[9], and a collection and recycling rate of 20%[10], this means that insufficient collection and recycling cause annual losses of more than 16,000 tons of cobalt. This is roughly equivalent to 10% of the world's annual cobalt production and more than the planned full-scale production of *the metals company* after 2030 (see Table 2-1). While this estimate is subject to various uncertainties, it does not include the recycling potentials provided by other battery applications such as notebooks, tablet-computers and e-scooters.

Although it is obvious that – in the next decade of technology shifts – recycling alone will not be capable of supplying all metals at sufficient quantities, it is also obvious that existing potentials are substantial and far from being fully exploited. Li-ion battery recycling is particularly underexploited and requires targeted interventions in many world regions.

A more holistic view on circular economy

The demand for raw materials – including those for Li-ion batteries – is also influenced by the way we design and use products. Low-quality and short-lived products are still widely sold in all world regions, as they appear to be cheap choices to consumers at first sight. But short product lifetimes

[9] Mobile phones are commonly equipped with Lithium-cobalt oxide batteries (LCO) with cobalt contents of up-to 25%. For this estimate an average battery weight of 39g with a cobalt content of 13.8% is assumed (Manhart et al. 2016).

[10] Some collection and recycling of LCO batteries (which is the most valuable type of Li-ion battery) occurs but is often sub-standard and under the radar of regulators (Manhart et al. 2022). In addition, it is known that some middle-income countries with developing regulation and enforcement achieve collection rates of up-to 20% (Hilbert et al. forthcoming).

are a major factor in the overconsumption of resources. And many short-lived products are even more expensive for consumers considering the costs for necessary replacement products.

Introducing minimum standard for durability and repairability can therefore have a significant effect on total resource consumption. In the context of Li-ion batteries, the EU considers introducing performance and durability requirements through its planned new Battery Regulation (European Commission 2020a). And beyond these aspects, further circular economy elements can jointly exert significant resource reduction and conservation leverage:

- Fostering shared use of products;
- Increasing the recycled-content of products;
- Fostering reuse and repurposing.

Particularly the latter aspect offers great potential to reduce the overall demand for battery raw materials: Many used batteries (e.g., from electric vehicles) still have a suitable quality and capacity for a second-life in other applications such as stationary power storage. While such repurposing of batteries has been extensively discussed, uptake of this concept still depends on political support, including clarification of liabilities in case of battery failures and accidents. It is also relevant to note that access to battery management systems (BMS) is an important pre-condition for detecting the status of health of used EV batteries and their modules. Therefore, universal access to the BMS could greatly facilitate battery repurposing, but is not yet state of the art.

Considerations on mining

A growing world population aiming to achieve the Sustainable Development Goals, including elimination of poverty (SDG 1), universal access to clean energy (SDG 7) and economic growth (SDG 8) will continue to strongly rely on raw materials. Sustainable cities and communities (SDG 11) and sustainable consumption and production (SDG 12) can certainly help to abate raw material demands as reflected in the sections above. But despite all efforts to speed-up circular economy, the world will, in the short- and mid-term, still rely on raw materials from mining. While there are multiple reasons to refrain from deep-sea mining, it is also important to properly mitigate negative environmental and social impacts from terrestrial mining.

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