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ENVIRONMENTAL IMPACTS OF EXTRACTION AND PROCESSING OF RAW MATERIALS FOR THE ENERGY TRANSITION

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Colophon

Environmental impacts of extraction and processing of raw materials for the energy transition

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Main findings

The Dutch raw materials strategy aims to improve security of supply of materials that are economically important for the Netherlands and the European Union. Addressing harmful impacts from extraction and processing is a prerequisite and one of the five key strategies put forward in the policy document. The increasing demand for primary materials for the energy transition is of specific concern. At the request of the Dutch Ministry of Foreign Affairs, this study provides an overview of environmental impacts commonly identified in mineral production (i.e. extraction and processing) for the energy transition, as well as potential explanatory factors of these impacts.

The energy transition is an important driver of the increasing demand for some critical materials and related environmental impacts in the producing countries

Renewable energy technologies are one of many areas that use critical materials. Globally, the energy transition will likely result in an overall reduction in mining activities, in the medium to long term, primarily due to a strong decrease in coal mining and increase in recycling of materials. Nevertheless, for some materials, the energy transition is a major driver of growth. In 2022, the renewable energy transition primarily used steel, aluminum, copper, silicon, graphite, zinc, nickel, chromium, manganese, lithium, cobalt, molybdenum, neodymium, and dysprosium. Most of these, except chromium, molybdenum, zinc, and steel, are on the EU's critical raw materials list. Important determinants of future growth in mineral demand are the long-term climate target (e.g. 1.5 °C or 2 °C), energy demand, the technology mix, and the rate of material recycling. Limited studies have assessed future developments in supply. Some studies expect that future mineral production is associated with less strict environmental policies, raising concerns about fairness, substantial environmental impacts, including climate change, biodiversity loss, and pollution.

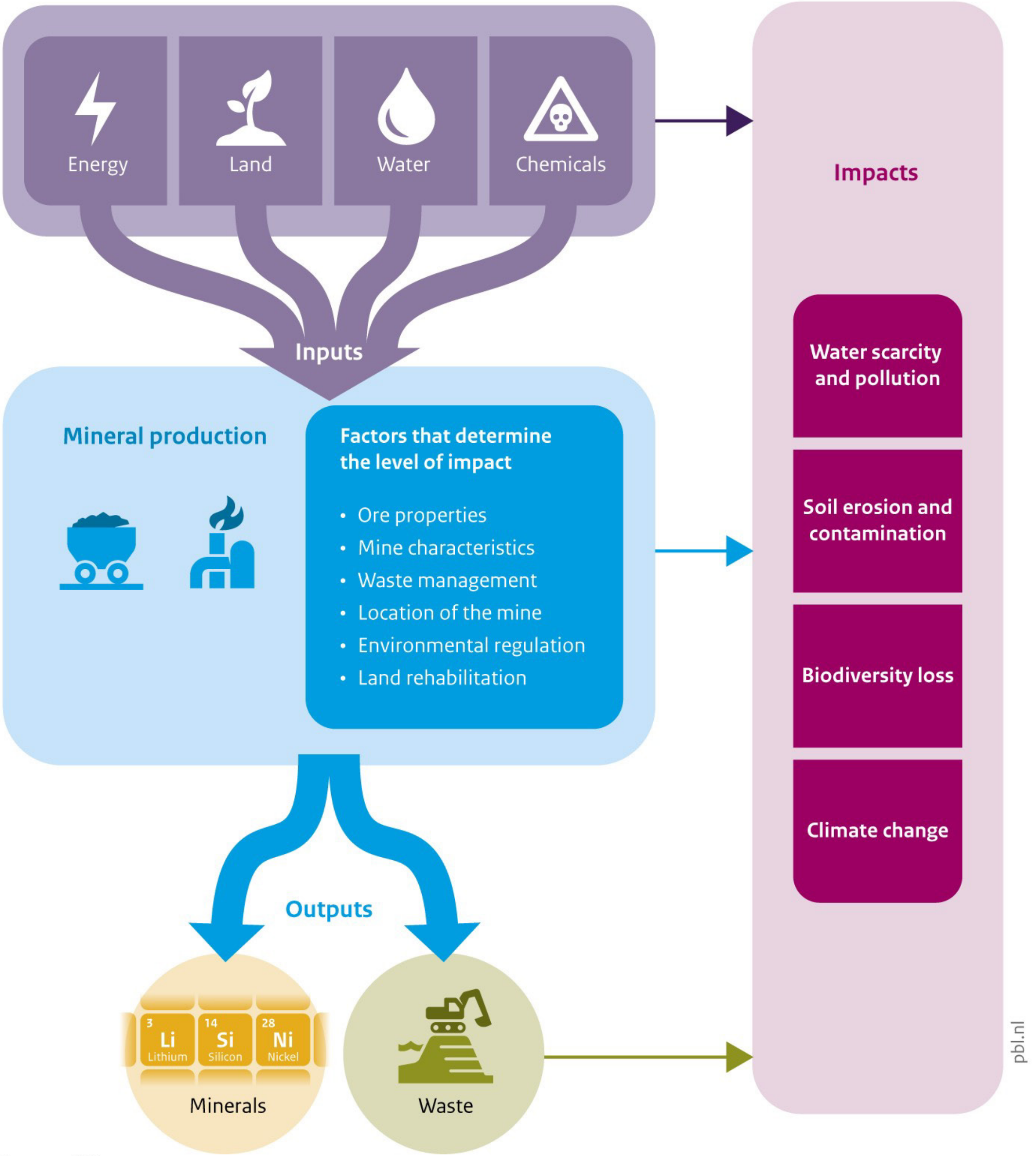
Most environmental impacts are caused by use of land, energy, water, chemicals and the generation of waste

Land use and land alteration related to mineral production not only stem from mining itself, but also from related developments, such as infrastructure, processing facilities and storage of large volumes of waste. Although, globally, the impact of mining on land use is smaller compared to logging or agriculture, its negative effects are profound and long-lasting. During resource extraction and further processing, large amounts of water, chemicals and energy are used. In addition, much waste is being generated, such as overburden (i.e. removed soil and subsoil), waste rock (i.e. unprocessed blasted rock) and tailings (i.e. residue from mineral extraction). Although tailings are often stored in large dams, risks of leakage of radioactive elements and heavy metals are high. These aspects all impact the environment in different ways (see Figure 1):

- **Water scarcity and pollution:** The main drivers of water scarcity are water extraction for ore processing and the dewatering of mines. Lithium and copper production, in particular, require large amounts of water, while around half of the global lithium and copper production is concentrated in areas that are already under high water stress. Regarding water pollution, the main drivers are inadequate waste management and land rehabilitation. Contaminated water may carry heavy metals and toxic elements downstream, also polluting these areas. This is mostly the case in the production of sulfide ores (e.g. copper, manganese, nickel and cobalt). Currently, around 23 million people are directly exposed to dangerous concentrations of toxic waste accumulating along riverbanks as a result of the extraction and processing of metals.

Figure 1

Environmental impacts and explanatory factors of mineral production



Source: PBL

- **Soil erosion and contamination:** Main drivers of soil erosion are mine development and crushing and milling of ore, while soil contamination is mainly linked to inadequate waste management. All mines around the world, together, cover around 100,000 km^2 of land area, while almost 1 million km^2 of land is overlaid with mining-related waste, which is more than the global total in urbanised area. Of specific concern are the large volumes of red mud generated for aluminium production, contributing to increased natural radioactivity and the presence of toxic elements in the environment. Around sulfide mines, acid mine drainage causes heavy metal contamination of topsoil and subsoil.
- **Biodiversity loss:** Biodiversity is impacted directly by remote and pristine areas being accessed and opened up and habitats being destructed during mine development. Mines lead to other local activities and, therefore, also have an indirect impact on biodiversity, such as through agriculture, logging, and poaching, and water and soil pollution and contamination. Nickel

mining, in particular, has a relatively large impact on biodiversity per tonne produced, mainly due to its proximity to areas of high biodiversity. Mining operations are increasingly encroaching on areas rich in biodiversity. Since 2000, about 8,500 km^2 of tropical and subtropical rainforests have been removed directly due to mineral production. When also taking indirect impacts of mining into account, globally, the affected area is estimated at about one third of all forests.

- **Climate change:** The primary driver of climate change related to mineral production is the huge amount of energy required for heavy machinery, smelting oxide metals and steel production. Of the total global energy-related greenhouse gas emissions, an estimated 10% stems from mineral and metal production. Other drivers are deforestation, ecosystem degradation and the chemicals with high embodied carbon used in processing. Silicon production has the largest climate change impact per tonne produced, mainly due to the high amount of energy needed for upgrading low grade quartz to high quality silicon.

A large part of the environmental impacts can be linked to ore properties, including the type of ore and the ore grade

The type of ore determines the processing route. Hydrometallurgy is generally used for oxide metals, such as aluminium and lithium, and requires large amounts of water and chemicals. Pyrometallurgy is generally used for sulfide metals, and requires a large amount of energy for heat. The ore grade (i.e. the concentration of the desired material per tonne of ore) strongly determines the amounts of energy, water and chemicals required to extract the material. Some minerals have naturally low ore grades (e.g. REEs), while for some minerals (e.g. copper) ore grades are declining. As a result more energy and water is required, and more waste is generated in extracting the metals.

Insufficient waste management can cause large-scale contamination that can continue for hundreds of years after mine closure or abandonment

Tailings often contain large amounts of heavy metals and chemicals. Seepage of chemicals from abandoned and active tailing dams and tailing dam failures cause large amounts of chemicals to infiltrate ecosystems downstream. Although small-scale and artisanal mining is far less energy-intensive than large-scale mining, it is associated with highly polluting practices. Because of the fluid characteristic of waste and the fact that it is unregulated, proper waste management systems are often lacking, leading to severe soil degradation and water contamination. It is estimated that, currently, about 11 million people around the world are affected by closed and abandoned mines, and 12 million by active mining activities. Without proper post-mining land rehabilitation, open-pit mines and tailings can remain a source of contamination for hundreds of years after mines are closed down or abandoned.

Indirect impacts of mining can be severe, including the opening up of pristine areas and pollution traveling long distances through air, water and soil

Mines are a pull factor for economic activities, further opening up the area. The development of mining infrastructure can lead to human settlement, increasing exploitation of resources and agriculture, further leading to biodiversity decline. Studies show that mining is taking place within the proximity of critical ecosystems, affecting up to 16% of the remaining wilderness areas and driving deforestation.

Other indirect impacts are caused by pollutants dispersed through air, water systems and soil. Sediments may disrupt river systems, and acid mine drainage from the mining of sulfides may contaminate soil and groundwater for many kilometres. These indirect impacts are under-quantified and insufficiently regulated.

Mandatory and broader regulation is important in reducing and preventing environmental impacts

Environmental regulation encompasses various aspects of mining operations, from pollution control to post-mining land rehabilitation. This includes implementation and enforcement of environmental impact assessments, emission standards, regulation of waste management and water use, and land rehabilitation requirements. From an environmental perspective, all levels of governance have been too soft or are not taking into account all the risks. As a result, most mining companies are neglecting indirect/accumulative impacts and are abandoning mines without implementing land rehabilitation. For example, environmental assessments conducted for the regulatory approval of mining projects focus mostly on the immediate effects of new or expanding mining projects, disregarding the broader, long-term consequences. Another example is a lack of regulation on mine site rehabilitation. This is important to ensure that mining companies incorporate a rehabilitation plan and make a serious effort to restore the land, economically or environmentally, strongly reducing the risks of lingering impacts, such as further sedimentation, acid mine drainage and pollution of downstream water bodies.

There is a large knowledge base on the environmental impacts of mineral production, but some important gaps remain

Research on the environmental impacts of mineral production is important to improve sustainability in international supply chains. While existing knowledge already provides a clear reason to act, several knowledge gaps and research challenges persist:

- In scientific literature there is a lack of comprehensive research on the impacts of metals. This includes a bias towards the analysis of climate change impacts, and while some metals, such as copper, have been extensively researched, others (e.g. molybdenum, silicon, graphite, and REE) have been relatively neglected. Furthermore, planning and exploration are mostly overlooked in scientific impact studies, while the legacy and cumulative impacts of mining are not understood well enough yet to get a good overview of the overall risk of metal mining on different ecosystems
- Scientific environmental assessment methods for metals, such as of Life Cycle Assessment (LCA), have not been streamlined, making it hard to combine or compare. The co-production of different metals from the same mine creates challenges with the allocation of impact to the individual minerals.
- Legislation on reporting of mining projects and impacts is still mostly voluntary, which is partly why there still is a lack of transparency and related unavailability of spatial data from mining companies. Data on abandoned mines are lacking, too, as well as on artisanal and small-scale mining activities, specific locations and the associated environmental impacts. This limits the ability of researchers to assess the true extent of mining-related environmental issues.

1 Introduction

There are growing concerns about the supply of raw materials for strategic sectors, such as renewable energy, health care, digital sectors and the defence industry. These are related to the rapidly growing demand for minerals, challenges around rapid upscaling of mining activities, and geopolitical challenges as mining and refining is concentrated in a limited number of countries. Furthermore, extraction and processing of minerals is associated with a range of negative environmental and socio-economic impacts, depending on the methods and processes used (IRP, 2019; Lèbre et al., 2020; IEA, 2021).

To address these concerns, the Dutch Government developed the national raw materials strategy (EZK et al., 2022). This strategy serves as a starting point for the Netherlands' contribution to the EU Critical Raw Materials Act (CRMA) and the promotion of Dutch interests. It aims to improve security of supply of materials that are economically important for the Netherlands and the European Union. Addressing harmful impacts from extraction and processing is one of the five key strategies put forward in the policy document. The other strategies are circularity and innovation, sustainable European mining and refining, diversification and knowledge and monitoring.

Materials for the energy transition are of specific concern. While the energy transition will very likely result in an overall decrease in the scale of mining activities on a global level, primarily due to a strong decrease in coal mining and increase in minerals recycling, substantial energy transition-related mining activities will most likely remain for decades to come (Nijnens et al., 2023). A range of studies project a significant increase in demand for minerals for the clean energy transition (i.e. IEA, 2021; Van Exter et al., 2021; European Commission, 2023b). As mining and refining of these materials is very energy-intensive and requires large amounts of water and chemicals, it can contribute to climate change, pollution of air, water and soil, and the loss of nature and biodiversity (IRP, 2020).

At the request of the Dutch Ministry of Foreign Affairs this study provides an overview of potential environmental impacts caused by critical mineral supply chains for the energy transition. The report is structured as follows:

- Chapter 2 discusses what materials are critical for the energy transition and important to monitor from an environmental impact perspective, where they are mined, and their projected growth in demand.
- Chapter 3 provides an overview of the environmental impacts that are commonly identified in the production (i.e. mining and refining) of these materials, the production processes with the most important impact, the scale of the impact, and the materials that contribute the most.
- Chapter 4 discusses potential explanatory factors for these impacts, their main characteristics and how they affect impact.
- Finally, Chapter 5 provides an overview of knowledge gaps with respect to the environmental impacts of mineral production.

In Chapter 2, the analysis is based on mining data from the United States Geological Survey (USGS) and recent scenario studies on mineral demands. Chapter 3 employs recent comprehensive scientific reviews to estimate the magnitude of effects within each designated impact category.

Also, systemic reviews of environmental assessments were collected to find information about the effect per metal, in various impact categories (i.e. water consumption and contamination, biodiversity loss and climate change). This information was then combined with production data from the USGS to estimate the overall effect of each metal in year 2022. Chapter 4 brings together recent scientific studies and grey literature about the main drivers of these impacts. Finally, we identified some important gaps highlighted in the literature, which are discussed in Chapter 5.

The study does not address deep seabed mining, non-metallic minerals, secondary material production or the socio-economic implications of mineral production. Although it has a global focus, reference to low- and middle-income countries is made where relevant.

This research is part of a broader research on the sustainable and just supply of raw materials.

2 Materials for the energy transition

The production of renewable energy technologies, electric vehicles, and storage capacity all require large amounts of materials. This section discusses the raw materials that are critical for these technologies and important to monitor from an environmental impact perspective. It discusses where these materials are mined, as well as the projected future demand and production, with a specific focus on low- and middle-income countries.

2.1 Critical materials

Metals are not critical in themselves. Criticality is rather a construct of demand- and supply-side factors (e.g. Schrijvers et al., 2020). These factors are both dynamic, as they change over time, and context-dependent, as they can differ strongly between countries and regions. The European Commission has created a list of critical raw materials (CRMs) for the European Union, based on the importance of materials for the EU economy and the risk of supply disruption (European Commission, 2023b).[1] This list is reviewed and updated every three years. With its proposal for a European Critical Raw Materials Act (European Commission, 2023a), the European Commission has also introduced the concept of strategic raw materials (SRM). These materials are additionally characterised by their importance for strategic sectors (e.g. renewable energy; digital, aerospace and defence technologies; significant gaps between projected growth in demand and current supply; and difficulties of scaling up production). The current EU list includes 34 materials, 32 of which are labelled critical and 16 strategic (European Commission, 2023b). Around 20 materials on this list are important for renewable energy technologies.

However, the environmental impact of material production — the focus of this study — is not determined by the supply risk but rather by the volume of the ore that is mined (Section 2.2), what is being mined, and where and how this is mined and processed (Chapters 3 and 4). The 10 most-used materials for renewable energy products in 2022, based on their net weight, from high to low, are copper, silicon, graphite, zinc, nickel, chromium, manganese, lithium, cobalt and molybdenum (IEA, 2023). The IEA 2023 study excludes the base materials aluminium and steel. Aluminium is in high demand for electricity networks and structures for solar panels, and steel is important as construction material across a broad range of renewable energy technologies (IEA, 2021). Many studies also point to rare earth element (REE; especially, neodymium and dysprosium) as indispensable for, for example, wind turbines and electric motors (Gielen, 2021). Except for chromium, molybdenum, zinc and steel, all these materials are on the EU CRM 2023 list.

2.2 Mineral supply and demand

In the last 20 years, the global mining industry has seen significant expansion. Global production of fossil fuels, metal ores and industrial minerals increased by around 50%, from 11.3 billion tonnes in 2000 to 17.3 billion in 2020 (Jasansky et al., 2023). Certain minerals have experienced even more

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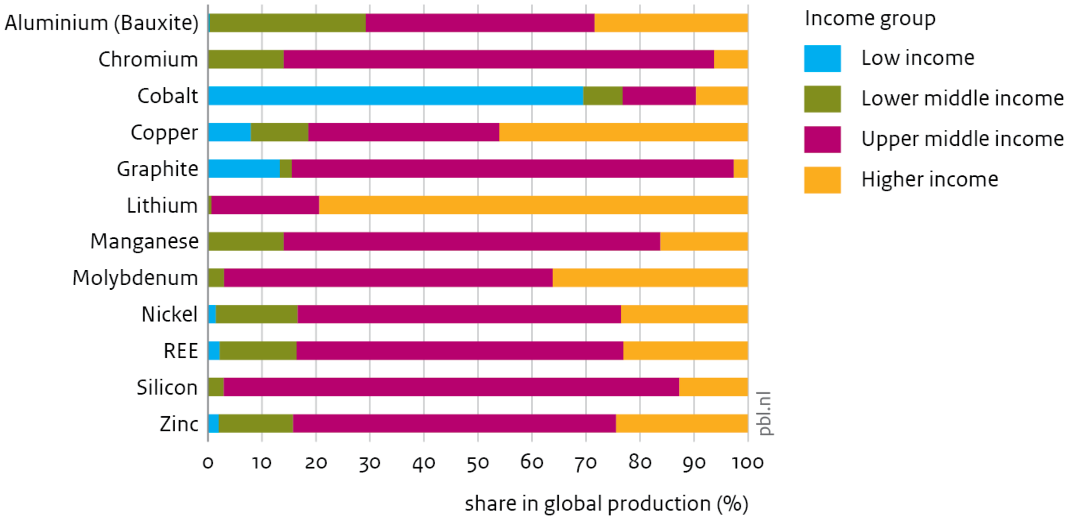
[1] Economic importance is determined by the raw material need and added value of relevant sectors. Supply risk of disruption is based on global and EU supply concentration, EU import reliance, input of secondary materials, and technical substitutability. As the European Union has a far lower availability of minerals in its territory than do China and the United States, many more metals and minerals are currently perceived as ‘critical’.

rapid growth, such as iron ore with a 151% increase, and aluminium with a 166% rise within the same timeframe. This trend is expected to continue, especially for metal ores, partly due to the rising demand for clean energy technologies and widespread electrification efforts.

Table 2.1 provides an overview of current global demand for selected materials for clean energy technologies in 2021, as well as 2022 global production, reserves and resources.[2] While for several materials clean energy technologies are responsible for only a very small share of total global demand (e.g. aluminium, steel and chromium), for some materials they are a major driver of growth. For example, in 2022, renewable energy technologies accounted for 16% of total demand for nickel, 40% for cobalt and 56% for lithium, up from 6%, 17% and 30%, respectively, in 2017 (IEA, 2023). At the same time, global estimated reserves in 2022 are enough to cover more than 100 years of current use for clean energy technologies. Furthermore, as minerals are becoming more valuable, reserves are increasing, as more resources become economically minable, and resources increase as more effort is put into mapping and exploring minerals. For example, between 2012 and 2022, the world's lithium reserves grew from and estimated 13 to around 26 million tonnes, and total resources from 40 to 98 million tonnes (USGS, 2014, 2023).

Figure 2.1

Global mining activity per income group, 2022



Source: USGS (2023)

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[2] 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 (CIM, 2014).

Table 2.1
Global raw material demand for renewable energy technologies, 2021 (IEA, 2023) and total production, reserves and resources, 2022 (USGS, 2023)

	Demand (kt)	Production (Mt)	Reserves (Mt)	Resources (Mt)
Aluminium (Bauxite)	-	380	31,000	55,000–75,000
Chromium	181	41	560	12,000
Cobalt	68	0.190	8.3	25[1]
Copper	5,736	22	890	2,100[2]
Graphite (natural)	587	1.3	330	> 800
Iron	-	1,600	85,000	230,000,000
Lithium	73	0.13[3]	26	98
Manganese	174	20	1,700	NA
Molybdenum	26	0.250	12	25.4
Nickel	475	3.3	> 100	300
REEs	13	0.3	130	NA
Silicon	765	8.8	NA	NA
Zinc	585	13	210	1,900

[1] Only terrestrial resources; [2] undiscovered resources estimated at 3,500 Mt; [3] excluding US production;

Table A.1 in the Appendix provides an overview of mineral mining in low- and lower middle-income countries. For most minerals, low- and lower middle-income countries together account for around 15%–20% of global production in 2022 (Figure 2.1). Low-income countries are dominant in cobalt mining with the Democratic Republic of Congo (DRC) producing around 70% of global cobalt. DRC also produces a significant amount of copper, and Madagascar and Mozambique are important graphite producers. Relatively more mining takes place in lower middle-income countries, especially bauxite in Guinea, but also manganese in Ghana, and molybdenum and nickel in the Philippines. However, besides lithium and cobalt, most minerals by far are mined in upper middle-income countries (e.g. Brazil, China and Russia). Several high-income countries also play an important role in global mining (e.g. Australia, Canada and Chili). Australia and Chili are dominant in lithium mining, and Chili also plays an important role in the mining of copper and molybdenum.

2.3 Future mineral demand and production

A range of studies have looked at future demands for minerals for the clean energy transition. The best-known and most-cited projections are from the International Energy Agency (IEA, 2021, 2023). Other recent projections are from the World Bank (Hund et al., 2020) and the German Raw Materials Agency (Marscheider-Weidemann et al., 2021). For an overview of older studies see IRP (2020), Gielen (2021) and Watari et al. (2020). Although these projections are all subject to major uncertainties (e.g. IEA, 2023; Wang et al., 2023), they all conclude a phase-out of most fossil fuels and significant growth in demand for metals towards 2040/2050, especially for battery-related materials (e.g. cobalt, graphite and lithium) but also for manganese, molybdenum and REEs (Table A.2 in the Appendix). For example, IEA (2021) projects an increase in lithium demand by a factor of 13 to 51, between 2020 and 2040, and for cobalt and graphite by a factor of 6 to 30. Also the share of clean energy technologies in total demand for specific materials is projected to increase. Where renewable energy technologies accounted for around 20% of total demand for copper and neodymium in 2022, and 56% of total lithium demand, these shares are projected to increase to 45%–50% and even 90%, respectively, in a scenario that reaches net-zero CO_2 emissions for the energy sector by 2050 (IEA, 2023).

An important source of uncertainty about the growth in demand across the different studies and scenarios is the anticipated climate ambition (e.g. 1.5 °C or 2 °C). A more stringent climate target not only requires larger deployment of renewable energy technologies by 2050, but also much faster deployment and thus higher demand already by 2030 (IEA, 2023). Other determinants include projected energy demand (driven by population growth, economic and technological developments, as well as behaviour), the technology mix (e.g. deployment of wind and solar, electric vehicles, CCS and negative emission technologies) and the choice of sub-technologies (e.g. dominant battery technology or choice of wind turbine). For example, to reflect the latest developments in battery technology, compared to IEA's 2021 projection (IEA, 2021), the 2023 update includes a larger share of lithium iron phosphate and an earlier switch to high-nickel chemistries, with a notable downward impact on cobalt demand (IEA, 2023). Finally, also the rate of material recycling is an important source of uncertainty. While in the short term minerals are stocked in an expanding renewable energy system, in the longer term, the decommissioning of end-of-life technologies provides opportunities for reuse or recycling. Studies on future projections of secondary material availability are still scarce. Uncertainties in future availability of secondary materials relate to the lifetime of technologies, collection rate of discarded technologies, metal recovery rate, and the materials needed for future technologies (Deetman et al., 2021; Van Oorschot et al., 2022).

While there are many studies on future material demand for the clean energy transition, there is a lack of those that assess where these minerals are likely to be produced in the future (Watari et al., 2021). Based on detailed modelling for some minerals (i.e. iron, copper, zinc and lithium), combined with constant 2015 production shares for others, Watari et al. (2021) conclude that a significant share of mining activities will most likely come from countries with sometimes less stringent policies on environmental resource management, such as China, Russia, DRC and the Philippines. The unfolding mining boom, thus, may have a substantial environmental impact, including climate change, loss of nature and biodiversity and pollution of land, water and air. These impacts are discussed in more detail in Chapter 3. In addition, although not part of this study, weak to failing resource governance comes with the risk of misappropriation of funds, rather than benefiting local communities (Watari et al., 2021). Combined with existing poverty, vulnerability to environmental change and fragile economic development, this complicates progress in human development and well-being for people at national and local levels.

3 Environmental impacts of mineral production

As shown in Chapter 2, the energy transition will require a huge increase in the extraction and processing of specific minerals, which could cause substantial environmental impacts. This chapter synthesises the latest insights around these environmental impacts. It focuses on quantified impacts and zooms in on metals with a high impact. The chapter is structured as follows: Section 3.1 discusses the different stages in mine development and mineral production. Subsequently, Section 3.2 discusses the environmental impacts linked to these stages. Four broad types of environmental impacts are discussed: water scarcity and pollution, soil erosion and contamination, the resulting loss of nature and biodiversity, and climate change.

3.1 Stages in mineral production

Figure 3.1 shows an overview of common stages in mineral production, including the life cycle of a mine and the different steps from ore extraction to the actual metal ready to be used in the production of renewable energy technologies. The environmental impacts differ between these various stages. The life cycle of a mine includes:

- **Prospecting and exploration** aims to identify economically viable mineral concentrations. This stage involves assessing the resources, evaluating potential environmental and social impacts, and estimating costs and potential returns (IRP, 2020). This can be a combination of public and private efforts. This stage typically takes between 1 and 10 years but sometimes many more years.
- **Planning and construction** is about designing the set-up, mining processes and recovery plan. Once everything is assessed and designed, the construction phase starts. Overburden is removed, infrastructure and processing plants are constructed, as well as additional aspects, such as facilities for employees. This phase takes about 1 to 5 years on average.
- **Operation** is the stage where the ore is extracted. This can take 2 to 100 years, sometimes more.
- **Mine closure and post-closure** is about land rehabilitation after the mine is economically exhausted. It is about economic and/or ecological recovery of the mine site. Since 1977, land rehabilitation has become a regular part of modern mining practices, mainly in western countries (IRP, 2020). In low- and lower middle-income countries, however, there is often a low level of compliance regarding the rehabilitation obligation (Listiyani et al., 2023). Closure takes up to 5 years, on average, but post-closure impacts may increase over time and linger for hundreds of years.

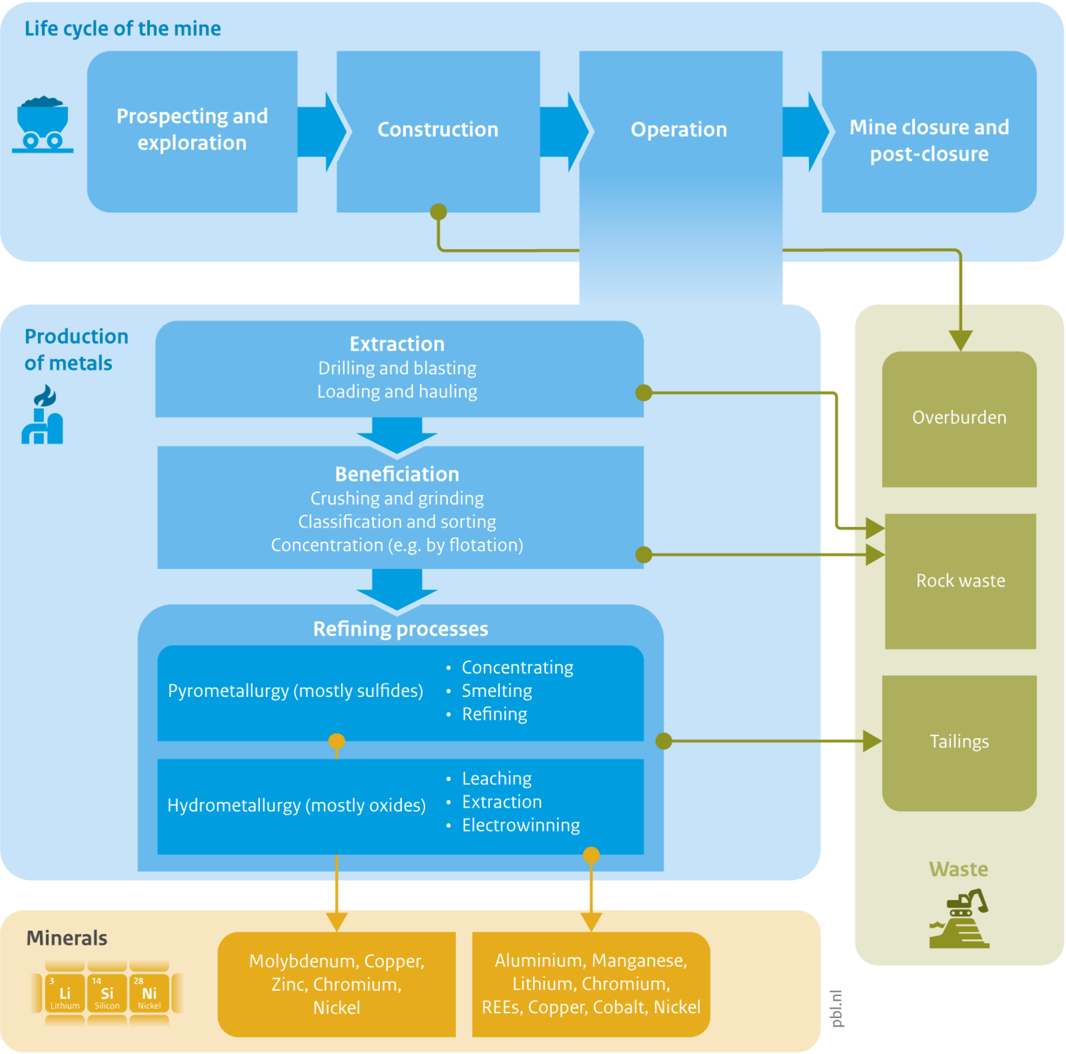
When the mine is in operation, the following steps can be distinguished:

- **Extraction** of metallic ores involves various techniques of surface and underground mining, with the choice of method depending on factors, such as the deposit's characteristics, location, size, depth, and grade. All mines contain multiple metals of various ore grades. A metal is however only extracted if it is economically viable at that moment in time, which is why many metals end up in waste piles.

- **Beneficiation** is the process of concentrating the ore, separating gangue material from valuable material and producing a tradable ore concentrate (with tailings as waste). Usually, this happens at the mine site, and involves crushing, grinding, classification, sorting, separation, and concentration (e.g. by flotation). Gangue is typically the most worthless and undesirable material. This stage generates the most waste.
- **Refining** is the recovery is metals from the concentrated ore. Different processing routes can be distinguished. Sulfide metals can be extracted from their ores in pyrometallurgical processes (i.e. thermal treatment of metals). Oxide metals can be recovered through hydrometallurgical processes (i.e. the use of aqueous and chemical solutions to recover metals). The hydrometallurgical route for oxidic metals (e.g. copper ores), also called SX-EF (solvent extraction-electrowinning) combines beneficiation and processing. Lithium is currently mostly extracted from brine, requiring slightly different processes than hydrometallurgy. This stage often occurs in countries other than where the metal has been mined.

Figure 3.1

Common stages of mineral production for renewable energy technologies



Source: PBL

3.2 Impacts of mineral production

The environmental impacts of mineral production stages are generally caused by the use of land, energy, water and chemicals and the production of waste. Mine development requires land for the mine itself, but also for other uses, such as infrastructure, processing facilities and waste. During resource extraction and further processing, high levels of water, chemicals and energy are used. In addition, much waste is being generated in the form of overburden, waste rock and tailings. Overburden and waste rock are often stored in heaps and piles while tailings are often stored in dams to reduce the risk of leakage of all kinds of radioactive elements or heavy metals. When the mine is closed or abandoned, environmental impacts can linger or even aggravate if rehabilitation of the site is not done well.

Section 3.2 discusses the impacts of mineral production of the selected metals. The information is mainly based on recent scientific overview studies and syntheses of environmental assessments with a global perspective. Per impact category (described in the sections below), first the primary drivers are discussed, followed by the scale of impact on a global level. Where available, the impact per tonne of metal produced from the literature is presented. To determine total impact of the demand in a year, impact per tonne is multiplied by total metal demand from IEA (2023), as presented in Table 2.1. The metals with a high impact are discussed in more detail, in the text boxes. Note that demand for iron/steel as a resource for renewable energy products is unknown, while it is likely the largest material input in terms of volume.

3.2.1 Water pollution and scarcity

Water is impacted in two ways by mining: extraction and processing of ore and poor waste management can cause water pollution, and excessive water consumption can cause water scarcity. Of particular concern are the water-related effects of mining operations on hydrological systems, as local freshwater sources are vital to provide the necessary amounts of clean water for both human and environmental requirements. Due to increasing social, economic, and environmental concerns surrounding water impacts, a growing body of research has begun quantifying the water footprint of energy products (Madaka et al., 2022).

Water pollution

Globally, there are large concerns about the pollution of water bodies caused by mining operations and closed/abandoned mines. In mine development, biomass is removed, increasing sedimentation resulting in disturbed aquatic ecosystems. During mining and post-mining phases, water can become contaminated (Beck et al., 2020). Water quality deteriorates due to discharges of contaminated water, for example, from retention ponds or uncontrolled run-off in the mining area (UNEP, 2013). Insufficiently treated toxic effluent waters generated during hydrometallurgical processing can directly pollute surface waters. Such effluent waters often contain hazardous chemicals used in mineral ore processing, such as cyanide, mercury, arsenic, lead and zinc. In addition, these waters may have high levels of acidity. The most severely contaminated discharges typically occur shortly after operations have ceased, when artificial dewatering has stopped and groundwater levels recover (Byrne, 2011). Coulthard and Macklin (2003) reveal a remarkably prolonged duration of contamination; more than 70% of the deposited pollutants persist in river systems for over 200 years following the closure of a mine.

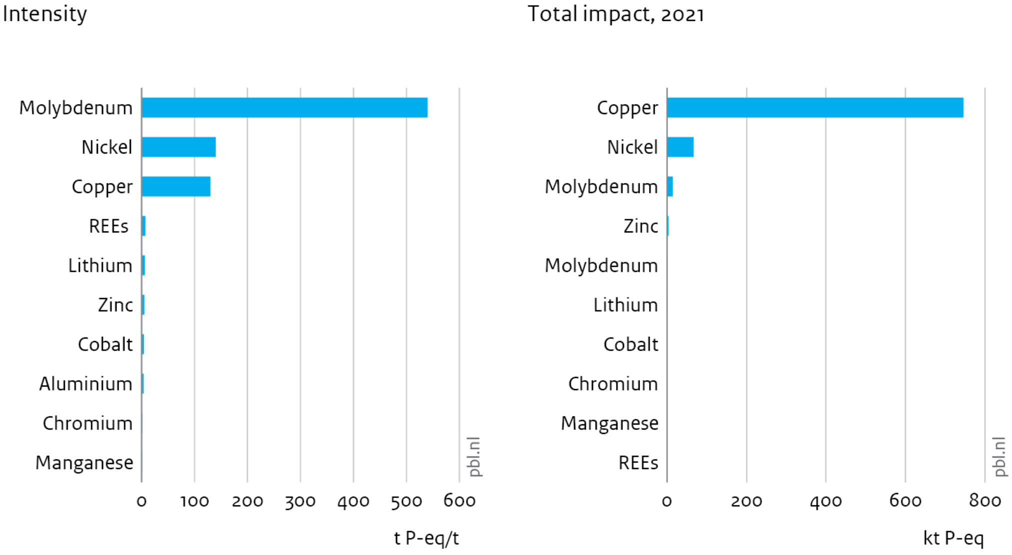
Metal mining has been responsible for significant adverse effects on aquatic ecosystems, including heavy metal contamination, acidification, sediment buildup, reduced oxygen levels, salinity increases, and declines in calcium levels, all of which have damaging impacts on the overall health of aquatic ecosystems (Beck et al., 2020). Worldwide, 479,200 km of river channels and 164,000 km^2 of floodplains are currently affected by metal mining (112,400 km^2 from inactive mines and 52,000 km^2 from active mines) (Macklin et al., 2023). About 23 million people, 6 million livestock and 66,000 km^2 of irrigated land are directly exposed to dangerous concentrations of toxic waste accumulating in riverbanks due to metal mining activity. These numbers will only increase due to the ramping up of metal mining and decreasing ore grades. According to Macklin et al. (2023) Oceania, Europe, North America, and South America predominantly experience the effects of abandoned mines, while in Africa and Asia, it is particularly the active mines that contribute more to pollution.

Studies have demonstrated that water contamination from mining activities can have severe and widespread consequences for fish habitats and populations downstream of mining sites, including areas used for aquaculture and fisheries (Affandi and Ishak, 2019).

Life cycle analysis (LCA) allows for the evaluation of the potential environmental impact of metals across various categories throughout their entire life cycle, from raw material extraction to end-of-life disposal (i.e. ‘cradle to grave’). In Figure 3.2, systemic review studies collected results of LCAs of mineral production for selected metals. According to these very generic results, molybdenum causes the highest amount of eutrophication per tonne, while copper has the highest impact globally (steel was not taken into account in these studies). In Box 3.1 the reasons these metals cause such high pollution levels is explained. Freshwater eutrophication is just one of the toxicity effects, other effects, such as acidification or radioactivity, have not been quantified.

Figure 3.2

Freshwater eutrophication from material production for renewable energy technologies



Source: Rachid et al. (2023) and IEA (2023)

Box 3.1: Metals with a high water pollution impact

Molybdenum

Molybdenum sulfide is mined as a primary product and as a co-element of copperbearing ores. Molybdenum and rock waste are exposed to the environment through mining processes, tailing dams and poorly rehabilitated abandoned mines. Through acid mine drainage, it causes eutrophication in interconnected water bodies. In addition, molybdenum mining can cause high metal content to enter the environment, which is highly toxic to plants and animals. Research on levels of exposure and impacts are still limited (Frascoli and Hudson-Edwards, 2018). Similar effects are seen for other sulfide ores (e.g. copper and nickel).

Rare Earth Elements

REEs are named rare because of their low ore grade, which means that more effort is needed to extract them. There are two common methods for REE mining, both of which release toxic chemicals into the environment (Nayar, 2021). The first involves creating leaching ponds where chemicals are added to extracted earth to separate metals, but these ponds can leak toxic chemicals into groundwater. The second method uses pipes to pump chemicals into the ground, also leading to leaching ponds and environmental issues. Both methods generate large amounts of toxic waste, including dust (average of 13 kg/t REEs), waste gas (approx. 10,000 m^3/t), waste water (75 m^3/t), and radioactive residue (1 t/t). This can be attributed to the fact that, when REE ores are mixed with other chemicals in leaching ponds, they contaminate air, water and soil. Of particular concern is the occurrence of radioactive thorium and uranium in rare earth ores, leading to severe and harmful health consequences. For every tonne of rare earth elements produced, approximately 2,000 tonnes of toxic waste is generated. The environmental impacts are mainly caused due to weak environmental regulations for mining of REEs in, for example, China.

Water consumption and scarcity

In mineral production, water is required for processing ore (i.e. grinding, floatation, separation etc.) and dust suppression. Water is both important for hydrometallurgical and pyrometallurgical processes. Water is mostly extracted from groundwater, streams, rivers, lakes or commercial water service suppliers. There is a strong correlation between the amounts of water used per kg mineral and the ore grade (Meissner, 2021). The lower the ore grade, the more water is needed to extract the specific metal. Also dewatering of mines can have tremendous impacts. In Germany, for example, the only regions with physical groundwater scarcity are those with lignite mining.

Global water footprints of metals have not yet been fully studied (Madaka et al., 2022). Globally, when compared to other sectors, mining accounts for a relatively small proportion of total water use. Meissner (2021) calculated that mining of metals[3] accounts for about 0.1% of total water consumption. This sounds like a small amount, but mining can severely affect freshwater resources on local or regional scales. This occurs when water consumption surpasses the carrying capacity of the region, which is determined by the amount of available water and level of dependence of the surrounding ecosystems and communities (Meissner, 2021). Groundwater lowering for mining further aggravates water stress with far stretching regional effects. According to WRI (2024), at least

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[3] Besides the metals included in this report (i.e. bauxite, cobalt, copper, manganese, molybdenum, nickel and zinc), Meissner included iron, lead, uranium, gold, palladium, platinum and silver. Graphite and silicon were not included.

16% of the critical mineral mines, deposits, and districts on land are in places with high or very high water stress. These are areas where farming, industry, and homes often use a large amount or all of the available water. In figure 3.3 depicts an overview of the average freshwater use of several metals. Around half of global lithium and copper production is concentrated in areas of high water stress (IEA, 2021).[4] This demand creates competition for water between mining and other uses, including agriculture and nature. In water-stressed areas, new mines are increasingly opposed by local communities as open pit mines risk endangering the main source of water for the communities (Schoderer and Ott, 2022). Box 3.2 further elaborates on why lithium, REEs and copper production are important contributors to water scarcity.

Box 3.2: Metals with a high water scarcity impact

Lithium

In 2022, there were eight fully active mines that produced lithium from continental brines. More are likely to open before 2030 (Vera et al., 2023). Lithium is currently extracted primarily from continental brines and hard rock ores, with continental brine resources being more abundant. The process of extracting lithium from continental brine involves open air evaporation, resulting in the loss of significant amounts of water, ranging from 100–800 m^3 per tonne of lithium carbonate. Although the brine water is not suitable for drinking or agricultural purposes, research indicates that extracting large amounts of it can lead to fresh water seeping into brine aquifers and blending with the salt water. This process can lead to the saltwater contamination of fresh water sources and reduce the availability of surface and groundwater nearby (NRDC, 2022). Suitable continental brine locations are limited, with a significant portion located in drier regions, such as the Lithium Triangle in Latin America, which covers parts of Chile, Argentina and Bolivia and contains over half of the global lithium supply.

REEs

Golroudbary (2022) estimated the water consumption of the primary production of REEs. This was 0.42 million m^3 in 2010 and is expected to reach 0.91 million m^3 by 2030. Most of the water consumption is attributed to Neodymium and Cerium.

Copper

Water use in copper production depends on processing techniques. For example, pyrometallurgical processing of copper ores is estimated at 91 m^3 of groundwater per tonne, while hydrometallurgical processes consume about 70 m^3 per tonne (Madaka et al., 2022). In addition, tailing dams are a large cause of water loss.

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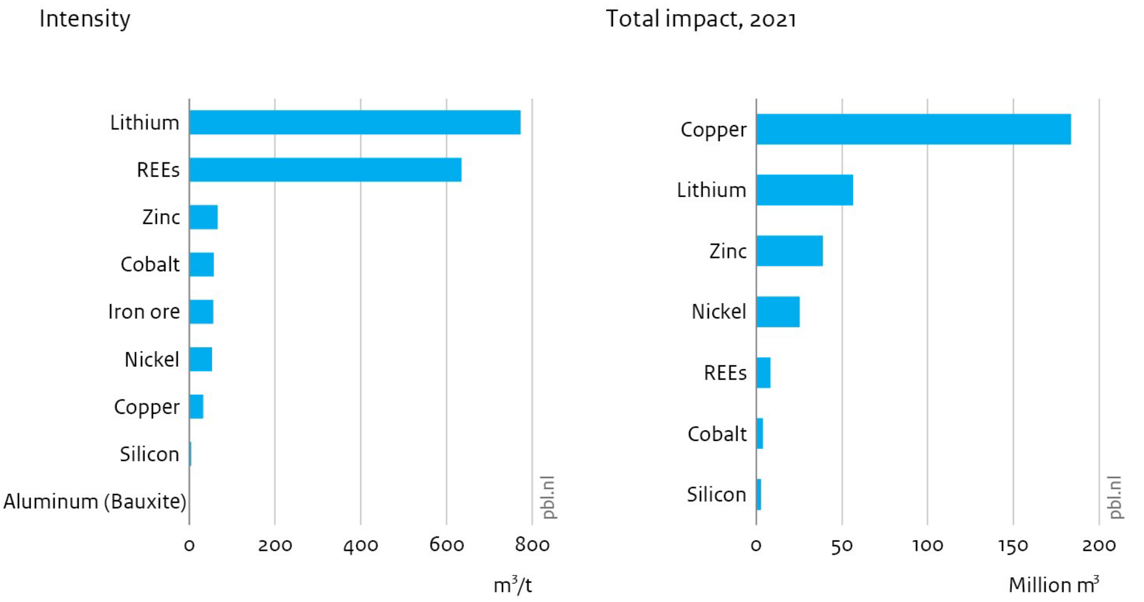
[4] High water stress is defined as the ratio of total water withdrawals over the total available surface and groundwater supplies above 40%.

Figure 3.3

Freshwater use from material production for renewable energy technologies



Source: Rachid et al. (2023) and IEA (2022, 2023)

3.2.2 Soil erosion and contamination

Soil is impacted by mining in two ways: soil erosion linked to mine development and crushing and milling of the ore, and soil contamination mainly linked to poor waste management. Although these are increasingly seen as important impacts, quantitative analysis is scarce.

Soil erosion

Mining processes significantly reduce soil particle sizes, thereby aggravating the erosion by rainfall, run-off or wind. The erosion process takes place when stripping overburden (i.e. soil and subsoil above the bedrock), blasting and excavating rocks and minerals, waste dumping, and reclaiming of the land after mining activities have ceased (Ramli et al., 2020).

The post-mining impacts result in changes in land morphology, topography and landscape. The landscape of post-mining sites often is uneven with deep holes and big piles of soil and rocks left from the mining process. Because of these changes, the land cannot be used for farming or building, and has an increased risk of avalanches (Listiyani et al., 2023).

Especially mining activities disturbing large areas of land may increase erosion rate up to several hundred times greater than from undisturbed areas. With satellite imagery, (Maus et al., 2022) estimated that globally mines cover around 100,000 km^2 of land area, including waste rock dumps, pits, water ponds, tailing dams, heap leach pads and processing infrastructure. This is about 0.07% of the total land area, to compare: the total in urban area covers about 0.51% of the total in land, globally (Kuang, 2019). It is safe to assume that the fertile topsoil and subsoils that were there before are lost. In addition, the number of mines abandoned around the globe is estimated to be in the hundreds of thousands (Ippolito et al., 2019). In many countries there is not enough information or regulation on land rehabilitation. This indicates that soil erosion continues after mining companies abandon the site.

There are no generic/global quantifications on how much soil erosion/pollution occurs around mines. However, many case studies indicate that further downstream, ecosystems and human health are also significantly impacted. In addition, high sediment loads in surface waters commonly lead to vast changes in aquatic ecosystems, such as turbidity that increases sediment loads in rivers and lakes, causing problems with both photosynthesis for plants and visibility for fish and other organisms. The overall impacts on soil health and biodiversity can be very significant for soil structures, reducing soil biota and disrupting hydrological processes. This can drastically reduce the number of plant species able to grow, changing habitats and, thus, the species they support, and leading to an increased risk of bio-accumulation for some contaminants (IRP, 2020).

Soil contamination

There is a consensus in the literature that, for soils, the consequences of metal mining have been largely overlooked, while mining is one of the most important sources of soil pollution (Chen et al., 2022; Kříbek et al., 2023). An important driver of such pollution is the generation of tailings. Abandoned mines cause acidity, metal solubility, and degrading ecosystems (Ippolito et al., 2019).

According to recent estimates, an area of around 1 million km^2 of our planet is now overlaid with mining-related waste from all types of mines (Macklin et al., 2023). This is about 0.67% of the total global land area and more than the total urban area. Since many of the richest geological deposits have already been exploited, deposits with lower grade ores are now being mined, causing larger volumes of tailings per unit extracted. Each metal brings its own type of contamination with it. Box 3.3 zooms in at aluminium, copper, nickel and cobalt.

Box 3.3: Metals with a high soil contamination impact

Aluminium

As alumina production has grown worldwide, there has been a corresponding increase in the environmental accumulation of red mud. This waste material, generated during the alumina production process, can vary from 0.3 to 2.5 tonnes for every tonne of aluminium, depending on the bauxite ore used. Annually, the rate of red mud generation is about 120 million tonnes. Managing this waste effectively is a critical concern for the aluminium industry, given the significant quantities of red mud produced. Notably, the industry contributes to heightened natural radioactivity and the presence of toxic elements in the environment, largely due to the expansive land needed for red mud disposal sites. The high alkalinity of red mud makes it extremely corrosive and environmentally harmful, leading to the classification of red mud as a hazardous waste in terms of its environmental impact (Ozden, 2019).

Copper, nickel, cobalt

Around copper, nickel and cobalt mines, heavy metals often accumulate on topsoil and subsoil (Chen et al., 2022). Sources include dust fallout from tailing facilities, leakages of solutions from tailing dams, emissions from smelters, and breakdowns from pipelines that transport slurry cause deposition of metals in sediments. Tailings can be large, for example, in the Zambian copper belt tailing facilities cover an area of more than 9125 hectares. Metals spread from these tailings (through air/water) and stay in soils for a long time, thereby posing (severe) health risks to the food chain of communities and animals around the mining site (Kříbek et al., 2023).

3.2.3 Biodiversity loss

Biodiversity can be defined as ‘species, genetic, and ecosystem diversity in an area, sometimes including associated abiotic components such as landscape features, drainage systems, and climate’ (Swingland, 2013). Mining poses serious but also very specific threats to biodiversity: it affects biodiversity through many different pathways and on all spatial scales (i.e. mining site, local landscape, regional and global), both directly and indirectly. Most research has focused on direct impacts, indirect impacts are understood to a lesser degree (Sonter et al., 2018).

Currently, exploration for minerals is still done in protected areas (Sonter et al., 2023). Mining practices drive biodiversity loss directly by accessing and opening up remote or pristine areas and direct destruction of habitat (e.g. fertile soils, grasslands, forests) during mine development. With the clearance of overburden and natural habitats to gain access to mineral deposits — as well as to build facilities for storage, processing and waste — biodiversity is literally removed.

More indirectly, in case mining is the primary reason for opening up a natural area for development, this leads to follow-up activities such as road development, construction, or even agriculture, logging, and poaching, all activities that cause further land-use change and fragmentation of habitats, with associated impact on ecosystem services and biodiversity. Mining also causes biodiversity loss through pollution of water and soils due to the failure of tailing dams, dumping of rock and chemical waste, and acid mine drainage. In addition, water consumption can aggravate water stress, also causing biodiversity loss.

With satellite imagery, the visible land use (e.g. infrastructure and urban expansion) is mostly included in biodiversity impact assessments (Tang and Werner, 2023). However, the overall impact of contamination of soils and water, spreading of sediments and uptake of water is not fully quantified in literature yet. The extent and severity of biodiversity loss depends on the specific mining activity and the vulnerability of the surrounding ecosystem.

Direct losses

A global data set of biodiversity loss associated with mining-related land use is lacking. Sonter et al. (2020) and Cabernard and Pfister (2022) combine spatial mining data (57,277 km^2 of mining area as identified in 2014) and biodiversity data.

In some cases, removing mineral substrate permanently removes ecosystems, due to the dependence of specific biota on these minerals (Sonter et al., 2018). In Brazil, for example, iron mining completely removes a wide variety of plant systems. Cabernard and Pfister (2022) roughly estimate that 0.02% of global species have become extinct due to direct mining activities. This is mainly attributed to mining of coal (26%), nickel (19%), precious metals (12%), iron (6%–12%), and bauxite (5%–10%). Overall, they conclude that 76% of total mining-related biodiversity loss can be attributed to metal production (assuming about 10% of coal is used for heat and electricity for metal production). A quarter of this biodiversity loss is due to steel production. Areas with high ecosystem value are mainly directly affected in Indonesia (nickel), Australia (bauxite) and New Caledonia (nickel). Other hotspots are caused by nickel mining in the Philippines and Cuba, bauxite in Suriname, Brazil and Venezuela, and iron in Brazil, China and Venezuela. Most impacts associated with copper occurred in Chile, Peru and Indonesia (Cabernard and Pfister, 2022). Similar studies underscore the fact that many mines are located in regions with high ecosystem value (Sonter et al., 2018), while exploration for minerals is still done in protected areas (Sonter et al., 2023).

In terms of terrestrial ecosystems, direct deforestation due to mining is mapped in a study by Giljum et al. (2022) and WWF (2023). According to their assessment, since 2000, about 8 500 km^2 of tropical and subtropical rainforest has been lost, directly, due to industrial mining — including expanding extraction sites, tailing storage facilities, waste rock dumps, and on-site facilities for processing and transport. Of this loss of tropical rainforest, 80% was located in Indonesia, Brazil, Ghana and Suriname (incl. coal mining).

It is important to note that impacts persist after mines are abandoned/closed and land rehabilitation is extremely important to safeguard biodiversity (Sonter et al., 2023).

Indirect losses

The impacts of mining processes on biodiversity extend across vast distances through various pathways. Assuming an average impact radius of 50 km around each mining property, Sonter et al. (2020) estimated that mining area coincides 8% with protected areas, 7% with key biodiversity areas, and 16% with remaining wilderness. These areas partly overlap and include both direct and indirect effects of mining. WWF stated that the mining sector is the fourth largest driver of deforestation, affecting one third of the world’s forest ecosystems when indirect impacts are accounted for (WWF, 2023). According to the IUCN Red List, mining currently threatens as many species as does climate change (11,000 and 12,000 species, respectively) (Sonter et al., 2023).

An example of impact pathways are other human activities developing around a mine. For instance, the development of mining-related infrastructure can attract human settlements, introducing new threats or intensifying pre-existing ones, such as over-exploitation through hunting and fishing, the introduction of invasive species, and the loss of habitat due to other land uses, such as agriculture (Sonter et al., 2018; Cabernard and Pfister, 2022). Sonter et al. (2017) showed that mining induces deforestation in the Amazon rainforest up to 70 km from mining sites, indirect deforestation can be 12 times greater than forest losses in mining areas.

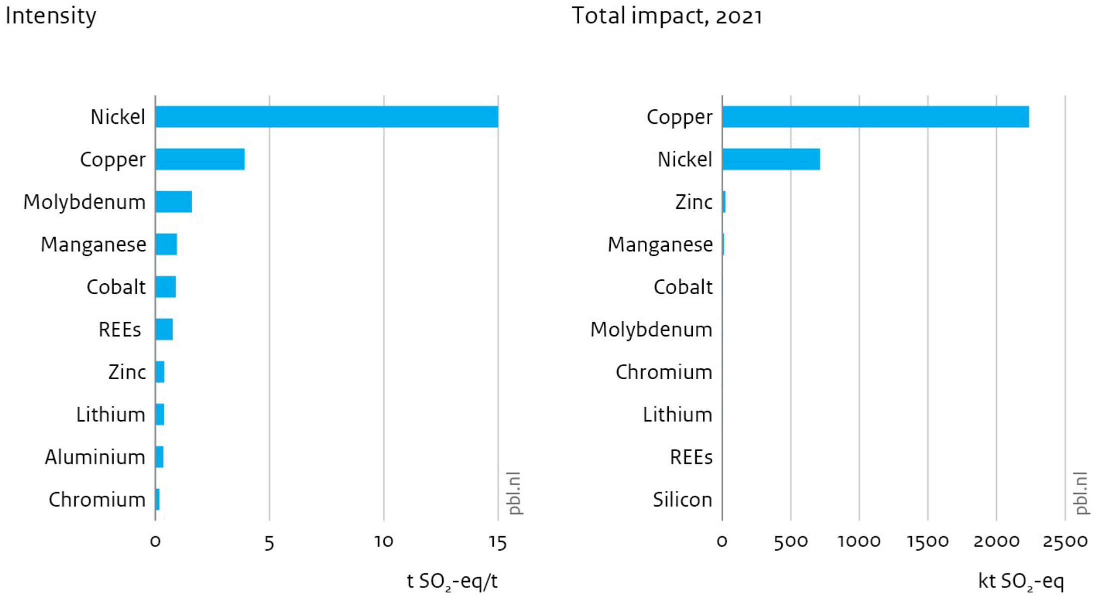
Another example is the export of sediment from higher areas, such as the Madre de Dios in Peru, which leads to the deterioration of ecosystems along interconnected rivers in Brazil. These processes result in the survival of only those species with a higher tolerance for the effects of large amounts of sediments (Dethier et al., 2023).

Lastly, an important cause for biodiversity loss is acidification of groundwater and soil. Quantification of terrestrial acidification is still understudied (Rachid et al., 2023). Terrestrial acidification is a consequence of acid mine drainage. This mainly occurs during the mining of sulfides, such as nickel, copper and molybdenum (Figure 3.4). Highly acidic waters can solubilise heavy metals and other toxic elements. Through rain and groundwater, these toxic and acidic streams spread through the environment, acidifying and contaminating the soils of terrestrial ecosystems.

When assumed that future mines will affect biodiversity the same way as current mines, threats will likely increase by 500% to 900%, by 2050, for some energy transition materials, such as cobalt and lithium (Sonter et al., 2023). The importance to understand and address these impacts is even higher when taking into account the trends of declining ore grades and that mines are mainly opened up in weak governance states with high biodiversity areas.

Figure 3.4

Terrestrial acidification from material production for renewable energy technologies



Source: Nuss and Eckelmann (2014), Rachid et al. (2023) and IEA (2023)

3.2.4 Climate change

Climate change is an important impact category from a global perspective. In terms of scale of impact, global metal production is one of the largest consumers of fossil fuels (Farjana, 2019). Overall, Azadi et al. (2020) estimate that greenhouse gas emissions associated with primary mineral and metal production were the equivalent of approximately 10% of the total global energy-related greenhouse gas emissions in 2018 (Azadi et al., 2020). This is a lot for one sector, especially since it contributes only 6.7% to global GDP.

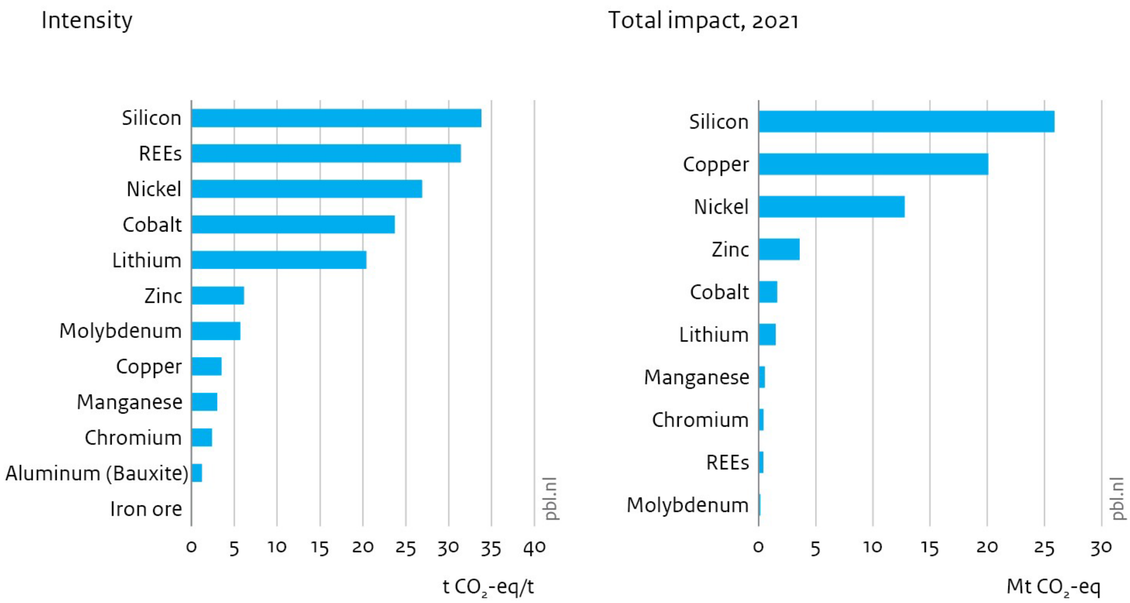
Fossil fuel consumption for the use of heavy equipment, electricity generation, large consumption of process heat and use of coking coal (i.e. for steel production) are the largest drivers of greenhouse gas emissions caused by the mining industry. With the increasing demand for metals, metal extraction goes deeper into the surface and lower ore grades are mined. The resulting increase in heavy machinery and equipment use requires more electricity and fossil fuels (Farjana, 2019). Of the most abundant geological reserves a great many have either undergone exploitation in the past or are presently being tapped into, many newly discovered ore deposits are complex and finer-grained, requiring more amounts of energy per ore deposit (Macklin et al., 2023).

After extraction, processing steps (e.g. smelting and refining) also emit many greenhouse gas emissions. For sulfide ores, energy use for smelting has the greatest impact because of the high temperatures this requires, which is also true for refining. For oxide ores, the consumption of hydrochloric acid and ammonium oxides often causes the largest impact, as the production of these flows requires large amounts of energy, causing a large embodied impact (Farjana, 2019). Mining also contributes to climate change through deforestation and ecosystem degradation (Norgate, 2010).

Silicon, aluminium, copper, zinc, nickel and manganese are the most important minerals contributing to climate change. The right graph of Figure 3.3 shows the total global production in megatonnes. For silicon, this is due to the large amounts of energy needed for upgrading low quartz quality to high quality silicon. For aluminium, copper, nickel, zinc and manganese), this large impact can mainly be explained by the high production levels, compared to the impact of, for example, cobalt (Table 2.1). Further elaboration on the cause of the impact of these metals is presented in Box 3.4.

Figure 3.3

Greenhouse gas emissions from material production for renewable energy technologies



Intensity

Total impact, 2021

Source: Rachid et al. (2023) and IEA (2023)

Box 3.4: Metals with a high impact on climate change

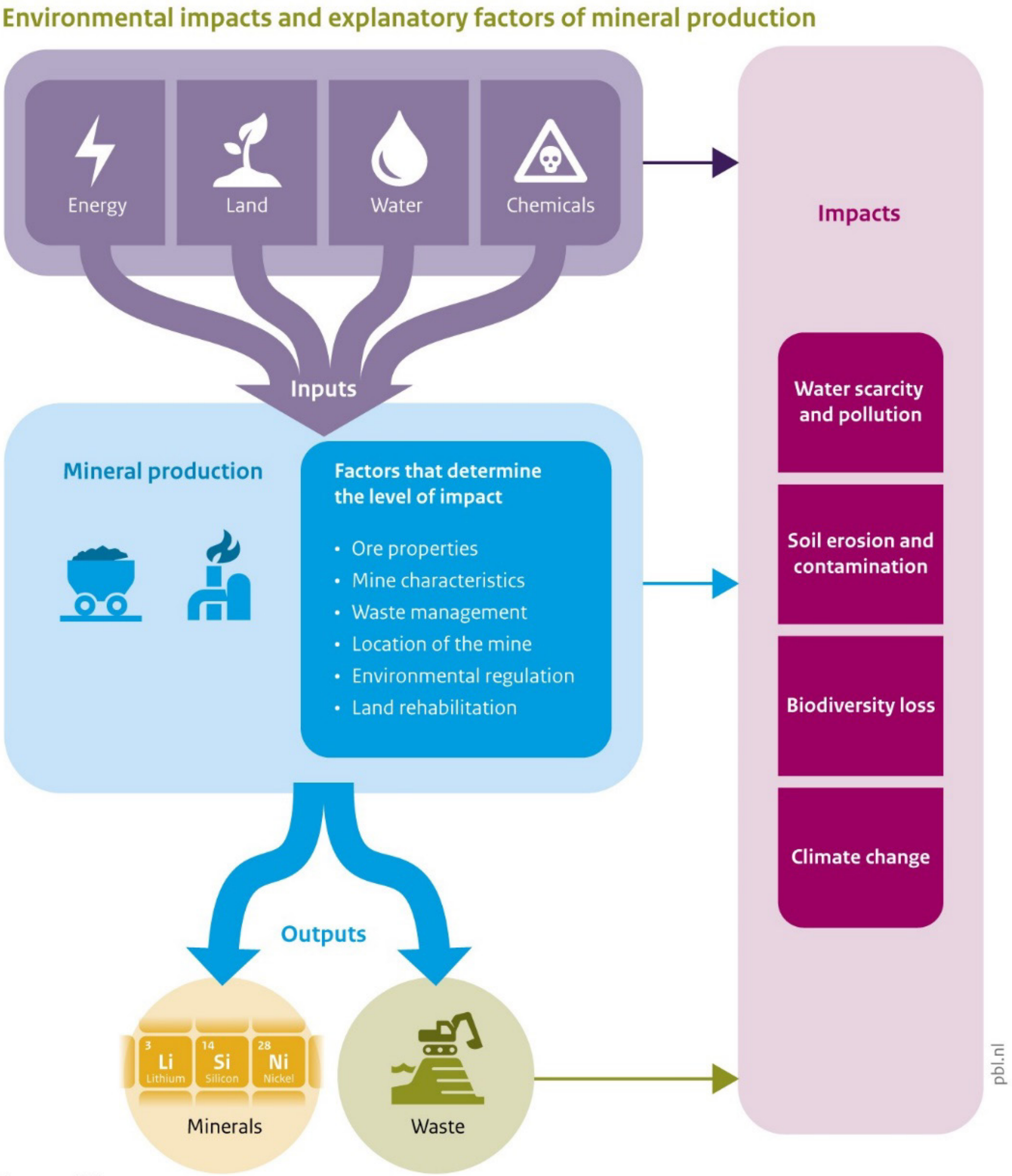
Silicon
The PV industry requires high-quality silica sand to produce metallurgical-grade silicon. Since high quality quartz deposits are scarce, lower quality silica sand is increasingly used (especially in China). As this requires more processing, it increases energy demand (Heidari and Anctil, 2022). The level of impact, however, is highly uncertain since a large part of the supply chain data of silicon is not traceable through official trade documents. A large share of quartz mining occurs illegally; it takes place in more than 70 countries and is the second most illegally traded product in the world. Current environmental assessments therefore likely underestimate the GHG emissions from silica extraction.

Nickel and cobalt
When a cobalt reserve is found, it is often found in combination with of copper and nickel, although cobalt is far less abundant than copper and nickel. The mining operations, encompassing land clearing, soil removal, tailings management, and ore loading and transportation, heavily depend on fossil fuels for their energy. Nickel and cobalt often have the same mineralogical characteristics, requiring similar beneficiation steps (Figure 3.3). Processing of these minerals relies on power plants as its primary energy source. These activities are the primary drivers behind the carbon emissions associated with the production of these metals (Adiansyah, 2023). In particular for nickel production, tropical forests are stripped — especially in Indonesia and New Caledonia, indirectly causing emissions of CO_2 (from loss of carbon sequestered in vegetation) and CH_4 (from loss of carbon in peat soils), and reduction in carbon uptake capacities. Around 70% of global cobalt is supplied from Congo, of which 20% is mined manually. From a climate perspective, this has a low impact since it requires less energy. However, from a human health perspective — which is outside the scope of this study — it has severe implications for the miners.

4 Explanatory factors of impact

As shown in Chapter 3, mineral production is associated with a range of environmental impacts, linked to the use of energy, land, water and chemicals. These impacts are largely context specific and depend on a range of factors, including ore properties, mine characteristics, waste management, mine location, and governance (Figure 4.1). This chapter discusses these explanatory factors in more detail.

Figure 4.1



Source: PBL

4.1 Ore properties

A large part of the environmental impact can be linked to the properties of the ore, including the ore grade, and mineralogical and chemical composition.

Ore grade refers to the concentration level of a particular material per tonne of mined ore. It is an important determinant of the quantity of ore mined and thereby of waste rock removed, the amount of energy used, the volume of process reagents required, and total land disturbed (Priester et al., 2019; Nassar et al., 2022). Energy use and related environmental impacts increase exponentially as ore grade in the mines decreases (Calvo et al., 2022). One of the most energy-intensive stages is crushing the ores, which is fuelled by electricity. Climate change impacts, thus, strongly depend on the regional electricity mix. In addition, ore grade decline results in larger volumes of waste rock and tailings, thereby increasing the risk of water pollution and soil contamination, while the larger surface area disturbed can lead to more significant impacts on biodiversity and soil erosion.

Mineralogical properties include hardness, size, and the presence of impurities. Harder or larger ore bodies require more energy for extraction and are thus associated with more greenhouse gas emissions. The presence of impurities or by-products can necessitate additional processing, requiring more energy and related environmental impact. Chemical properties refer to mineral composition, such as sulfide or oxide ores. Sulfide ores can lead to acid mine drainage, a major source of water pollution and soil contamination, with adverse impacts on aquatic ecosystems. This process can also release other harmful elements, such as arsenic, cadmium, mercury, selenium, and tellurium, into the environment. Oxide ores may require less harmful extraction methods but can still pose environmental risks if not managed properly. Rare earth ores may for example contain thorium, which emits harmful alpha rays when inhaled as dust, and nickel ores may have chromium as a by-product, which can become highly carcinogenic.

4.2 Mine characteristics

Mine characteristics relate to the type of mine (i.e. open pit or underground) and how it is organised (i.e. large-scale or artisanal and small-scale mining).

Around 90% of metallic minerals are extracted using surface or open-pit mining methods (Ramani, 2012). This involves removing surface vegetation and soil layers to access ore deposits, leading to extensive habitat destruction and biodiversity loss. The disruption of land surfaces increases the risk of soil erosion and water pollution. Underground mining involves digging tunnels or shafts to access ore deposits deep underground. It is less impactful with respect to land clearing but can cause land subsidence. Furthermore, underground mining typically requires more energy than open-pit mining, especially for ventilation and pumping out water, leading to higher levels of greenhouse gas emissions. The risk of water contamination can also be significant, particularly if acid mine drainage occurs.

Large-scale mining (LSM) involves the extraction of minerals using advanced technologies, and substantial capital investments. It contributes significantly to global greenhouse gas emissions due to heavy machinery, large-scale land disturbance, and energy-intensive processing. It can lead to large-scale soil disruption and water pollution. The large land-use footprint can also lead to significant habitat destruction and loss of biodiversity. In contrast, artisanal and small-scale mining

(ASM) often involves labour-intensive, low-technology mineral extraction and processing (Box 4.1). It occurs mostly in low-income countries. Artisanal mining is commonly considered to involve only individuals or families and is purely manual, while small-scale mining is more extensive and usually more mechanised (UNEP, 2013). The fluid and unregulated nature of ASM leads to a broad range of environmental consequences that affect large areas. This can result in widespread surface-level impacts, making it challenging to evaluate and oversee these effects effectively (WWF, 2023).

Although ASM is far less energy-intensive than LSM, it is associated with highly polluting technologies and practices, such as uncontrolled smelting and refining (releasing toxic gases, e.g. sulphur dioxide), use of mercury and cyanide (which are highly toxic chemicals) and improper waste disposal (tailings are often disposed of in rivers or on land). These practices often lead to severe soil degradation and water contamination, particularly from the unregulated use of toxic chemicals. For example, mercury and cyanide are highly toxic and can contaminate local water supplies, affecting both wildlife and human populations. They are challenging to control and toxic even in small amounts. They can travel long distances through air and water, contaminating soil and waterways, and eventually entering the food chain. These risks are for example disproportionately affecting women in sub-Saharan Africa, adding to the complex social and gender implications associated with ASM activities (IGF, 2017).

Box 4.1: Artisanal and small-scale mining (ASM)
ASM is commonly associated with precious metals, such as gold, and gemstones, but can also involve metals, such as copper, cobalt and nickel. In many low-income countries, ASM serves as a critical economic activity for local communities. It provides direct employment to miners, many of whom are from vulnerable social groups, including women and children. It is estimated that, in 2023, 44.6 million people worldwide are directly engaged in ASM, across 80 countries[5]. Countries with the largest number of ASM workers are India, China, Indonesia, DRC, Ethiopia, Ghana, Burkino Faso, Zimbabwe, Sudan and Tanzania. This number includes miners and workers involved in the extraction and processing of minerals. The number of people indirectly dependent on ASM, such as those in supply chains and supportive services, is significantly higher. In addition, over 150 million people depend on ASM for their livelihoods (Bank, 2020).

4.3 Waste management

Waste rock (i.e. unprocessed blasted rock) and mine tailings (i.e. residue from mineral processing), represents the largest solid waste flow, globally. Tailings storage facilities (TSFs), constructed to hold this waste, rank as the largest facilities worldwide (Aska et al., 2023). Disclosures from about 1743 TSFs, representing 36% of total commodity production, indicate that they currently hold a minimum of 44.5 billion m^3 of waste. However, this amount is growing, for example an estimated annual addition of 10 billion m^3 (or approximately 13 billion tonnes) of tailings had to be stored in facilities, during the 2019–2023 period (Aska et al., 2023).

As time passes, tailings undergo changes due to exposure to the environment, potentially releasing contaminants. It is estimated that the number of people affected by historical and active mining contamination is about 11 million and 12 million, respectively (Macklin et al., 2023). Storing tailings

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[5] https://www.delvedatabase.org/data

underwater can help prevent chemical changes by reducing their contact with the atmosphere. However, there is a risk of tailings dams failing and releasing large quantities of tailings into nearby river catchments, posing threats to human health and the environment. Tailing pond failures occur almost every year, and the frequency has been rising. Most failures are linked to heavy rainfall or earthquakes. The immense volume and environmentally sensitive nature of TSFs mean their collapse can adversely affect biodiversity for hundreds of kilometers downstream. Two notable TSF failures in Brazil, the 2015 Samarco disaster and the 2019 Brumadinho disaster, collectively discharged 50 million cubic meters of tailings into nearby water bodies. These incidents resulted in 289 deaths and caused irreversible harm to both aquatic and terrestrial ecosystems, as well as human communities (Aska et al., 2023). It is expected that the annual number of people affected by this is about 320 thousand (Macklin et al., 2023). The causes of failures vary by region, with hydroclimate as a common trigger in Asia and Europe, while earthquakes have been the main cause in South America. To mitigate these risks, effective tailings management is crucial (Kossoff et al., 2014).

4.4 Land rehabilitation

Land rehabilitation at closed or abandoned mine sites is an effective way of reducing the harmful effects of abandoned mining areas and to ensure these lands are used productively and efficiently. It is crucial for preventing continuous environmental impact for hundreds of years. However, especially in important mining regions in Africa, research and regulation on land rehabilitation lags behind (Festin et al., 2019). The main challenges in rehabilitating mine wastelands include issues such as soil compaction, abnormal pH levels (i.e. either too low or too high), poor water retention, erosion gullies, high soil density, and a lack of essential nutrients. The best approach to restoring the productivity of mine soil involves a mix of physical, chemical, and biological methods. The physical method reshapes the land, the chemical and biological methods improve the soil using different materials, such as biochar, compost, artificial fertilisers, synthetic compounds, various plants and even nanoparticles. Using these three methods together helps to improve soil fertility, boost microbial growth, and speed up the natural development of the ecosystem. However, before starting land rehabilitation, it is important to decide what the land will be used for, such as conservation, forestry, farming, dwellings and different types of recreation, or creating lakes or ponds. This decision should be based on thorough analysis and suitability studies of the land (Worlanyo and Jiangfeng, 2021). National research and development programmes and inventories of abandoned mines need to improve in order to increase the chances of mining site rehabilitation.

Box 4.2: Abandoned mines, risks in South Africa

In South Africa, there are 6,100 abandoned mines, and 2,322 of these are identified as high-risk mines. These high-risk sites are predominantly located in regions historically known for asbestos, gold, coal, and copper mining (Mhlongo, 2023).

Physical hazards to the public are an important risk, particularly for nearby communities. These dangers include injuries or fatalities in unused underground tunnels, drowning in flooded pits, or accidents involving unstable structures. Approximately 14,000 people, many of them illegal immigrants, engage in unauthorised mining activities in these mines. In addition, people build their homes on these hazardous lands due to a lack of available settlement space, thus exposing themselves to contaminated soil and the dangers of subsidence, shafts, and unstable, flooded pits.

4.5 Location of the mine

The location of the mine — for example, in rainforest, desert or mountain area — will determine the impact on the environment and nearby communities. Biodiversity impacts differ significantly across locations based on the unique ecological characteristics and species present. In areas with high conservation values as rainforests or wetlands, mining can have a disproportionately severe impact, as these areas often host a high level of biodiversity, including many endemic and rare species. Especially open-pit mining can lead to large-scale habitat destruction, fragmentation, and pollution (Seki, 2022). In arid regions, water use can significantly affect the availability of water for other sectors, such as agriculture and direct human use, as well as for nature. Similarly, mining in mountainous regions can lead to increased erosion and landslides, increasing human risks and disrupting the habitats of many species (Luo et al., 2018). Furthermore, impacts could be greater if new mining activities would be developed outside existing mining areas and/or far from current settlements, as this requires the development of new infrastructure, such as roads, railroads and ports. These developments can cause further changes in the landscape but can also open up areas for human settlements and other activities, such as hunting, fishing and agriculture (Sonter et al., 2018; Cabernard and Pfister, 2022).

4.6 Environmental regulation

Although the mining sector has increasingly adopted due diligence measures regarding the corporate responsibility to respect human rights, a similar emphasis on environmental due diligence is not as prevalent. While there are many international instruments and (mostly) voluntary initiatives such as the recent OECD handbook on Environmental Due Diligence in Minerals Supply Chains (OECD, 2023) and the Extractive Industries Transparency Initiative (EITI), they are not sufficient yet on their own to guarantee sustainable mining (IRP, 2020; Franken and Schütte, 2022).

One challenge frequently discussed in assessed literature is that supply chains of energy products are complex and often impossible to trace, thus complicating environmental regulation, such as International Corporate Social Responsibility standards from countries consuming end-products. Mineral supply chains involve numerous actors across various countries, each with differing regulations. Most minerals are undifferentiated goods, meaning they have the same characteristics regardless of extraction location, complicating their traceability back to individual mines. In addition, mineral aggregation points such as smelters, where materials from various mines are mixed, present a major obstacle for traceability. These traits make it difficult for companies to assess and mitigate environmental and human rights risks, and for regulatory bodies and civil society to hold companies accountable (Schöneich et al., 2023).

According to Franken and Schütte (2022) another challenge is the current uneven capacities for implementation of environmental regulations. For example in the artisanal and small-scale mining (ASM) sector in Central Africa, local production regions are remote, ASM producers are often poorly organised, monitoring is complex, and there is a lack of robust financing models on implementation costs. Broader social and environmental issues extend beyond the scope of these regulations (IRP, 2020).

Another issue often mentioned, related to the regulations themselves, is that environmental regulations do not tackle the indirect and accumulative impacts of a mine. For example, currently regulatory approvals often focus only on the immediate effects of new or expanded mining projects, overlooking the broader, long-term consequences that combine with other environmental stressors over time and space (Sonter et al., 2018).

Addressing environmental issues in mining requires considering environmental commitments within mineral governance and narrowing the gap between downstream expectations and upstream activities. Effective strategies, as identified in literature, include promoting a circular economy, supporting resource-rich countries in equitable value chain participation, implementing the Sustainable Development License to Operate (IRP, 2020), formalising ASM, fostering trust through standards like EITI, enforcing environmental impact reporting that includes local community perspectives, and employing a nexus approach in spatial planning to optimize the benefits of resources and protect biodiversity (Fenton Villar, 2020; IRP, 2020; Sonter et al., 2020). Further research is needed to tailor these strategies to specific contexts.

5 Knowledge gaps

Research on the environmental impacts of mineral production is a vital area of study, given the profound effects this industry has on natural ecosystems and human societies. While significant progress has been made in understanding these impacts, several knowledge gaps and research challenges persist.

The environmental impacts of mining are not fully understood

There is a lack of comprehensive research on the impacts of metals. In the literature, climate change dominates the assessment of mining impacts, occupying 64% of the LCAs (Rachid et al., 2023). This creates a bias since it neglects other vital aspects of mining, such as water use, waste management, exploration, and design, and land rehabilitation. For instance, major mining-related disasters often stem from poor tailings disposal practices and the infiltration of toxins into the soil and groundwater. The initial planning and exploration phases are also frequently overlooked in assessing environmental impacts. Some metals, such as gold and copper, have been extensively researched, while others, such as molybdenum, silicon, graphite, and rare earth elements, have been relatively neglected in the literature. Whether this gap should receive priority can be questioned, since mining impacts also depend on other factors than the type of metal that is mined. In addition, studies have warned that indirect, legacy and cumulative impacts of mining are not understood well enough yet to get a good overview of the overall risk of metal mining for the various ecosystems (Sonter et al., 2023). The impact of opening up and accessing pristine areas and contamination of soil and water affects nature and people well beyond the site and over an extended period of time is only partly known. This is also strongly visible in the fact that environmental assessments for regulatory approval of projects currently only look at a mine's direct impacts.

A complete overview of locations of mines is missing

The fact that mining operations are increasingly encroaching upon areas rich in biodiversity underscores the necessity for detailed mapping of land use within the global mining sector. Ongoing research efforts are dedicated to continuously updating the mapping of mining sites on a global scale. The most recent achievement in this area is the development of a comprehensive data set, which includes 44,929 mining sties, covering a total area of 101,583 square kilometres (Sonter et al., 2023). This data set encompasses a range of mining operations, from large-scale endeavors to artisanal and small-scale activities, including open pit mining, tailings dams, waste rock dumps, human-made water bodies, processing facilities, and other land features associated with mining activities. Essential geographic information is still missing. For example, throughout the past century, numerous mines have ceased operations for various reasons, yet a detailed and comprehensive database of closed and abandoned mine sites is lacking in many parts of the world. Consequently, the whereabouts of many of these mines have faded from public awareness. This absence of information impedes the ability of authorities to evaluate potential risks related to land and water pollution, as well as ground subsidence (Young et al., 2021). This information is needed for policy-making on global and regional scales for strategic locations for mines. Without strategic planning, the environmental impact of mining for renewable energy could be at odds with climate change mitigation benefits.

Environmental assessment methods for metals have not been streamlined or are not yet developed for mining

Environmental assessment methods for metals, such as of Life Cycle Assessment (LCA), have not been streamlined, complicating comparison or bundling of studies. An important complexity arises because frequently various co-elements (i.e. other metals) are mined from one mine, with variable economic values, leading to challenges known as multifunctionality issues (i.e. the allocation of impact to various co-products). As long as this is not solved, environmental impacts of co-products can be overestimated or underestimated. For the development of rules on environmental impact allocation, a political debate would be desirable, similar to that for agro-commodities. Also, there is a lack of research and metrics to properly assess the impact of metal mining on soils in LMICs. For example, research by Eijsackers et al. (2017) emphasises the challenges for arable soils in southern Africa due to mining. The current risk assessment procedures (often initiated by western mining companies), modelled on European and North American conditions, may not be suitable for the unique environmental conditions in Africa. Lastly, mining affects biodiversity at multiple geographic scales, from the mine site to global impacts. This includes the clearing of native forests, habitat fragmentation, and contributions to climate change. Improving performance-based metrics and understanding the impacts of mining on biodiversity are crucial steps to address these challenges.

Bottom-up data are incomplete and difficult to access

A lack of transparency from the side of the mining companies regarding their environmental impacts further hinders research efforts. The unavailability of crucial data from corporations limits the ability of researchers to assess the true extent of mining-related environmental issues. This causes the impacts to be underestimated. For example, it is assumed that more than 23 million people are living in floodplains affected by toxic waste from historical and ongoing metal mining. However, for this estimation, accurate data on mines and waste management facilities in China, India and Russia are lacking (Macklin et al., 2023). Steps have been made to improve reporting of impacts (e.g. by EITI and ICCM), but since this is voluntary, only some companies are seriously adopting these metrics. Research on artisanal and small-scale mining (ASM) activities in primarily low-income countries is still ongoing, as there is still a gap in knowledge on where ASM takes place and what the associated environmental impacts are (Tang and Werner, 2023). The varying status of ASM (formal/informal, legal/illegal) further complicates both the access to information on impact and the ability to regulate.

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Appendix

Table A.1
Mining in low- and lower middle-income countries, 2022 (USGS, 2023)

	Low-income countries *	**Lower middle-income countries** *
Aluminium (Bauxite)	*Mozambique, Sierra Leone*	Guinea (23%), India (4%), Tanzania (1%), *Côte d'Ivoire, Ghana, Iran, Pakistan, Solomon Islands, Vietnam*
Chromium	*Afghanistan, Madagascar, Sudan*	*India, Iran, Pakistan, Papua New, Guinea, Philippines, Vietnam, Zimbabwe*
Cobalt	DRC (68%), Madagascar (2%)	Papua New Guinea (2%), Philippines (2%), *Morocco, Vietnam, Zambia, Zimbabwe*
Copper	DRC (7%), *Eritra, North Korea, Uganda*	*Bolivia, Myanmar, India, Iran, Kyrgyzstan, Laos, Mauritania, Mongolia, Morocco, Pakistan, Papua New Guinea, Philippines, Tanzania, Uzbekistan, Vietnam, Zambia, Zimbabwe*
Graphite (natural)	North Korea (1%), Madagascar (8%), Mozambique (14%)	*India, Sri Lanka, Tanzania, Ukraine, Uzbekistan, Vietnam, Zimbabwe*
Lithium	-	*Zimbabwe*
Manganese	*Burkina Faso, DRC, Sudan*	Myanmar (1%), Côte d'Ivoire (2%), Ghana (5%), India (2%), Ukraine (2%), *Iran, Morocco, Egypt, Nigeria, Uzbekistan, Vietnam, Zambia*
Molybdenum	-	Iran (1%), Philippines (10%), *Mongolia, Uzbekistan*
Nickel	Madagascar (1%)	Philippines (10%), Myanmar, Morocco, Papua New Guinea, Venezuela, Vietnam, Zambia, Zimbabwe
REEs	*Burundi, Madagascar*	Myanmar (4%), India (1%), *Tanzania and Vietnam*
Silicon		*Bhutan, Egypt, India, Laos, Ukraine, Uzbekistan*
Zinc	*Burkina Faso, DRC, Eritrea, North Korea*	Bolivia (6%), India (6%), *Myanmar, Congo, Honduras, India, Mongolia, Morocco, Nigeria, Pakistan, Tajikistan, Uzbekistan, Vietnam*

** Numbers in brackets are global production shares; in italics means a production share of less than 1%*

Table A.2
Material demand for renewable energy technologies in selected climate mitigation scenarios

	Historical [1] (2021 demand as % of 2021 production)	**IEA** [1] (2040 demand as % of 2018 production)	**World Bank** [2] (2050 demand as % of 2018 production)	**DERA** [3] (2040 demand as % of 2022 production)
Climate target	-	1.5 °C	2 °C	2 °C
Aluminium (Bauxite)	-	-	9	-
Chromium	0	1	1	-
Cobalt	49	208	460	277
Copper	29	87	-	30
Graphite (natural)	53	315	494	74
Lithium	89	1437	488	400
Manganese	1	12	4	-
Molybdenum	9	2	11	-
Nickel	18	15	99	-
REEs	5	30	-	222
Silicon	7	25	-	-
Zinc	5	15	-	-

Source: (1) *International Energy Agency (IEA, 2023);* (2) *World Bank (Hund et al., 2020);* (3) *German Raw Materials Agency (Marscheider-Weidemann et al., 2021).*