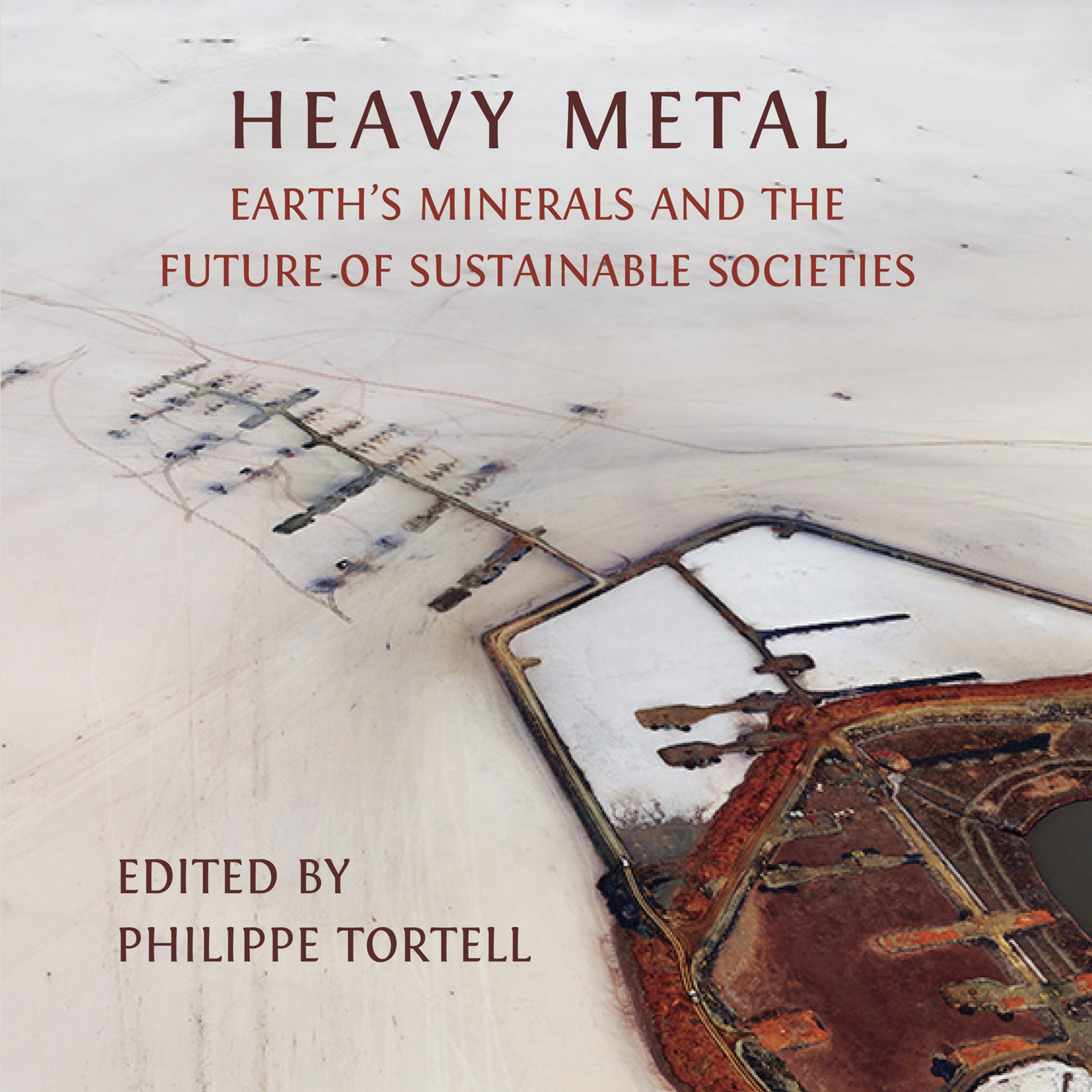
HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES



EDITED BY
PHILIPPE TORTELL

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The Future Demand and Supply of Critical Minerals

Werner Antweiler

Climate change has become a defining challenge of the twenty-first century. Tackling this challenge will require copious amounts of metals and minerals needed for renewable energy and low-emission transportation systems, including wind turbines, solar panels and electric vehicle batteries. At present, it remains unclear exactly how future mineral demand will grow, and whether these raw materials can be supplied in a socially and environmentally responsible manner. Addressing these questions is key to charting a path to future sustainability.

To begin, two important questions need to be answered. Which minerals are deemed critical, and which properties make them so? There are three specific characteristics that make a mineral critical for any country. They must be *necessary* for transitioning to a low-carbon economy and mitigating climate change; *essential* to the economic security of a country and its allies, with few or no substitutes; and *vulnerable* to supply chain disruptions or nation-state interference because of their concentration in specific locations of extraction and/or processing. The list of critical minerals evolves over time as their use changes, expands or declines. Currently, the most widely recognized critical minerals include lithium, nickel, cobalt, graphite and

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rare-earth elements (REEs). This list is not comprehensive and varies by country. Canada's list includes over thirty different elements.

Many of the economic and political risks associated with critical metals result from the concentration of metal deposits and refining activities in a small number of locations.[1] Further complexity in mineral supply chains results from the separation of raw material extraction and downstream processing. This uneven distribution gives significant market power to the limited number of private or state-owned companies that control a large fraction of mineral reserves and metal refineries. Take cobalt, for example. In 2022, the world's largest producing country was the Democratic Republic of Congo (DRC), which accounted for 68% of world supply.[2] By comparison, the next three largest producers, Indonesia, Russia and Australia, accounted for only 5.3%, 4.7% and 3.1%, respectively. The DRC's cobalt deposits are not only the world's largest, but they also have higher ore concentrations than other locations. The situation is even more lopsided for the refining of cobalt. China's output of refined cobalt in 2022 was almost eight times that of the second-largest producer, Finland. Chinese mining companies also hold controlling stakes in the DRC's largest cobalt mines.

Some metals have a more diversified supply base. Of the twenty-two million metric tons of copper produced in 2022, the largest producer country (Chile) accounted for about 28%, and the second-largest producer country (Peru) about 12%. Lithium is produced either from concentrate (derived from hard-rock spodumene) or from precipitating brines. Australia and China respectively produce about 47% and 15% of global lithium from concentrates, while Chile produces about 30% from brines. REEs are a group of seventeen metals that includes neodymium, dysprosium, praseodymium and terbium, which are widely used in the motors of clean-tech applications. By 2010, China had cornered the entire REE market, with 95% of global production capacity. Other countries, notably the United States, responded by increasing their own REE production. Within a decade, China's market share had decreased to about 60%. New discoveries of REEs in other locations (Sweden, Turkey, India) may further reduce China's dominance of REE supplies.

Although the production of some metals may be distributed globally, the processing of mined materials into final products is more concentrated in certain countries, most notably China. This country alone accounts for about half of global copper smelting and refining, and more than half of global lithium processing. The processing of REEs currently also remains concentrated almost exclusively in China. The spatial separation of extraction and processing follows economic considerations, but in China's case it is also a result of an industrial policy that has championed the development of this industry. Whatever the motives for this policy—domestic economic growth or foreign policy ambitions—the resulting concentration of market power could adversely affect markets, and also become subject to political interference and gamesmanship. Amidst rising geopolitical tensions, China's dominance of metal processing has led to a closer examination of supply chain resilience.[3]

Economic dependencies can be reduced by diversifying and controlling potential supply chain risks. Many countries, including Canada, are developing critical mineral strategies that address these concerns. This has become as much a political as an economic goal, but it comes at a significant cost. Considerable investments would be required in Europe and North America to build resilient supply chains for critical minerals that would lessen import dependence. Some Western countries are also making it more difficult for foreign investors to acquire mining operations, with particular restrictions on foreign state-owned enterprises.

Global markets for commodities are defined by supply, demand, prices, investments and various external factors. The supply of mineral resources follows exploration and mine construction, which are influenced by current and expected future market prices. Additional financial risk comes from the fact that exploration activities may or may not bear fruit, and from the high capital costs of developing major mining projects. As with the fossil fuel industry, the mining sector has undergone repeated boom-bust cycles, where high prices trigger new investment, eventually followed by overproduction and falling prices. Despite these fluctuations, metal and mineral prices have remained remarkably steady (in inflation-adjusted terms) over the past century, as exploration has not yet reached the limits of physical scarcity. This long-term stability does not eliminate periodic and short-term price spikes. As an example, nickel prices, which have hovered between 10,000–20,000 US dollars per metric ton in recent decades, jumped to over 48,000 dollars per metric ton for a brief period in March 2022, following the invasion of Ukraine by Russia, the world's third-largest nickel producer.

Over the past century, mineral demand has evolved gradually, driven by patterns of economic growth and development. In contrast, more rapid growth in demand is expected over the coming decades as we transition to renewable energy systems. The International Energy Agency (IEA) has estimated that mineral requirements will quadruple by 2040 if we are to reach the 2015 Paris Agreement targets limiting global temperature rise to 2°C. According to the IEA, the target of net-zero emissions (NZE) by 2050 would increase global mineral demand six-fold.[4] Even larger increases are projected for specific minerals that are essential for the clean energy transition; global output of lithium, graphite, cobalt, nickel and REEs could increase between ten- and forty-fold. These projections are based on currently dominant technologies and do not consider future technological innovations that could change demand for critical minerals.

Most of the projected mineral demand will come from batteries for electric vehicles and utility-scale electricity storage, as well as expansion of renewable electricity networks and transmission infrastructure. Wind and solar power require much larger amounts of minerals than conventional thermal power plants per megawatt (MW) of electricity. Solar power mostly requires copper and silicon. Wind turbines require zinc for the external structures, copper for connecting to the power grid (more so for offshore turbines) and a mix of REEs, manganese, nickel, chromium and molybdenum for electric generators and other components. Onshore and offshore wind turbines require between ten and fifteen metric tons of minerals per MW, with additional copper requirements for transmission grids. Massive expansion of renewable energy also depends on the development of electricity storage to address the intermittent nature of these supplies (the sun doesn't always shine, and the wind doesn't always blow). Among the competing technologies, lithium-ion batteries have taken an early lead, despite their high cost. These large mineral requirements pose a challenge for the expansion of renewable energy. As demand for these minerals increases, supply shortages could drive up prices and increase the cost of the clean energy transition.

Beyond the expansion of renewable energy, the transition to electrified transportation systems will require the replacement of millions of internal combustion engine vehicles (ICEVs) with battery electric vehicles (EVs). A typical EV, with a seventy-five-kilowatt-hour (kWh) battery, requires about five times as many metals and minerals as an ICEV. By weight, most of this extra demand will involve graphite, lithium, nickel, copper and cobalt, as well as some REEs, which are mostly used for motor components. Today, there are an estimated 1.5 billion motor vehicles in the world, with 20% of these in the United States alone. If each new EV requires about one hundred and sixty kilograms of metals and minerals, replacing only one-tenth of the world's vehicle fleet would require an additional metal demand of twenty-four million metric tons. For comparison, current metal demands in the global economy require worldwide production of cobalt, copper, graphite, nickel and lithium ranging from about one hundred thousand metric tons (lithium) to about twenty-five million metric tons (copper).

New technologies could partially offset the high expected mineral demand associated with EVs. Current EVs use lithium-ion batteries with a fluid electrolyte. New types of batteries are now emerging with lower mineral requirements, including lower-cost lithium-iron-phosphate (LFP) batteries, which do not contain nickel, cobalt or manganese. Other new technologies are expected to improve energy density while reducing dependence on various minerals. As a recent example, the US-based company Sparkz opened the first cobalt-free battery factory in Livermore, California in 2022. High prices for REEs could induce similar substitution effects, as motors containing permanent magnets (with high REE requirements) can be replaced by asynchronous induction motors, which use copper and aluminum instead of REEs. Similar technological innovation could also provide alternatives for electricity storage, including vanadium flow batteries and hydrogen electrolysis. Recently, sodium-ion and iron-air batteries have begun emerging as potentially lower cost and less critical alternatives to lithium-ion batteries. These batteries may be particularly suitable for stationary applications where energy density is less important than in mobile applications. The path of innovation will be influenced by the relative cost of material alternatives, and this will introduce uncertainty about the future demand for minerals.[5]

Can the global supply of minerals be scaled up to meet anticipated demand? And can this be done both rapidly and responsibly? The answer to these questions requires an understanding of global mineral reserves, industrial capacity and social and environmental impacts.

Global reserves of minerals are vast; according to the US Geological Survey, there are an estimated 22 million metric tons of lithium, 7.6 million metric tons of cobalt, 1.5 billion metric tons of manganese, 95 million metric tons of nickel, and 320 million metric tons of graphite distributed in countries around the world.[6] And future exploration will reveal new deposits as demand grows. For many metals, except copper,[7] physical scarcity appears unlikely over the short to medium term. A larger constraint on future mineral supplies will result from the need to rapidly scale up new industrial capacity for metal refining and processing. This enhanced capacity will follow demand and prices, although the need for various inputs, including energy and water, may shift competitive advantages among different countries.

For those new mining projects that go forward, the pace of development will not be fast, particularly for large mines. It often takes between ten and fifteen years or more of consultation, planning, permitting, financing and construction to build and begin operating a large mine. Governments should not allow shortcuts through this process, nor should they weaken social or environmental standards for the purpose of expediting projects. Although the development of small-scale mining operations could happen on much shorter timelines,[8] these operations will only be able to supply a fraction of anticipated future metal demands. Scaling up future mineral *extraction* will take more time than is envisioned in Canada's critical mineral strategy; the timeline for scaling up mineral *processing* and downstream manufacturing appears more achievable.

If mining activities cannot scale up rapidly, demand will exceed supply and prices will rise. Higher prices could slow down the energy transition, but they will also spur innovation in alternative technologies or applications that require fewer minerals. The upside of high prices is a greater incentive for recycling, and for the development of more mineral-efficient technologies. Higher prices will not necessarily upend the clean energy transition, but may instead channel the transition into more sustainable directions.

The rapid expansion of mining activities will inevitably lead to increased social and environmental impacts. Such impacts, rather than resource availability *per se*, may be a primary constraint on the future development of the minerals industry, as local communities reject proposed developments. It will become critical to ask how the sector can be transformed to minimize any negative effects.

Among the environmental threats posed by mining, the impacts on water systems are among the most significant.[9] Indeed, water is one of the defining environmental challenges for future minerals growth. Consider the example of Chile, which has the world's largest reserves of copper and lithium, most of which are concentrated in the arid regions of the Atacama Desert in the north of the country. Approximately two million liters of water is needed to produce one metric ton of lithium, which is evaporated from large salt ponds. For copper, 90,000 liters of water are needed for each metric ton produced. Large-scale water use by mining operators can add to local water stress, competing with drinking water needs and agricultural irrigation.

Processing the ore produced at mining operations also generates copious amounts of waste in the form of tailings, a slurry composed of wastewater and solid particles that is fed into an impoundment or enclosure made of earth dams.[10] The dams must be constantly maintained during the life of the mine and beyond. In rare cases, catastrophic failure of these dams can result from poor design or maintenance. The breach of a tailings pond at the Mount Polley Mine in British Columbia in August 2014 spilled an estimated twenty-five million cubic meters of water and tailings into nearby lakes and creeks, impacting local drinking water and salmon spawning grounds. The breach of Vale's Brumadinho tailings pond in Brazil in January 2019 inundated a local community and caused 270 fatalities. Senior Vale staff were indicted on murder charges, and the company was ordered to pay a seven-billion-dollar settlement.

Amidst growing water scarcity, water resources need to be better managed even in the face of higher costs. Instead of treating wastewater in tailings ponds, slurries can be filtered, thickened and dried, and the residual dry tailings can be stored more safely.[11] Dehydrating slurry requires energy, which adds cost, but this method can also save money in the long term by reducing insurance rates and remedial costs during mine closure. Water recovered from wastewater treatment can be reused, decreasing the demand for freshwater, and freshwater can sometimes be replaced with saltwater, or saltwater treated by desalination. The technical possibilities are vast, but the associated higher costs need to be internalized by markets. In recent years, water scarcity has already prompted the development and application of various water-saving technologies. This trend is expected to continue and accelerate.

Ultimately, environmental sustainability will depend on the ability to recycle minerals rather than continuously extracting new sources from the ground.[12] Kickstarting the recycling industry for future minerals is therefore an essential ingredient of the critical mineral strategies of all governments. In the long term, a large share of minerals will have to come from recycled sources. Hydrometallurgical processing of lithium-ion batteries (leaching with acids and metal separation using solvents) and pyrometallurgical alternatives (pre-treatment and reductive smelting) are already well developed. Direct recycling (disassembly, lithium enrichment and heat treatment) could eventually improve recovery rates and lower costs. These technologies are evolving rapidly.

The need for greater environmental stewardship must go hand in hand with the protection of individual and community well-being in mining-impacted regions. History is full of cautionary tales where resource extraction projects have jeopardized or destroyed traditional economic and social foundations of local and Indigenous communities.[13] Indigenous communities around the world—whose ancestral (and often unceded) lands are subject to significant mining activities—have too often been left out of decision-making, and deprived of ownership rights through colonialism or misdirected governmental paternalism.[14] With the development of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), there is now a globally recognized mandate for free, prior and informed consent (FPIC) in the development of any new mining project. Increasingly, UNDRIP is being incorporated into the legal framework of countries around the world, who are enacting national and regional laws implementing its principles into resource development projects. The explicit consent agreements mandated by such laws will be a cornerstone of the future minerals industry. Such agreements promote collaboration, define due process for environmental assessments and provide certainty for investors.[15] Relationships between mining companies and local communities can also be strengthened by joint infrastructure projects (for example, water treatment), benefit sharing agreements and co-ownership. Through such partnerships, mining projects can create pathways for Indigenous-led mining operations, with long-term economic benefits to communities.

One can imagine a number of different pathways for the supply of critical minerals to meet growing global needs. Scaling up mining around the world will certainly bring significant new challenges, including geopolitical risks, environmental hazards and growing social impacts. Meeting these challenges will require new approaches based on cross-sector and international collaboration.

New industry standards are beginning to evolve out of best practices adopted by some mining companies. The International Council on Mining and Metals (ICMM) fosters collaboration among mining companies and global organizations (including the United Nations) in the development of industry standards. As an example, the Global Industry Standard on Tailings Management was developed in the wake of the catastrophic tailings pond breach in Brumadinho, Brazil. This standard aims for 'zero harm to people and the environment' across all phases of project development, and requires mine operators to implement specific measures to prevent catastrophic failure of tailings facilities.[16] The Initiative for Responsible Mining Assurance (IRMA) offers independent, third-party assessment and certification of industrial-scale mines, holding them accountable to international standards for the design, operation and management of tailings facilities.[17]

Greater transparency of the global mining industry is needed to allow buyers and investors to make informed decisions that include a careful assessment of potential environmental and social impacts. For example, the Global Investor Commission on Mining 2030 is an investor-led initiative that is trying to develop a consensus about principles for socially and environmentally responsible investment in the mining sector.

Due diligence takes time and effort, and some have argued that this would result in unacceptable delays in the development of future mining projects. This inherent tension is difficult to resolve, but decarbonizing our economies cannot come at the cost of creating other large-scale environmental problems, or infringing on the rights of Indigenous communities on whose land mining often takes place. The key to meeting sustainable development goals in mining will lie in certification: a global standard for determining adherence to sustainable mining practices throughout the entire supply chain. To avoid a 'race to the bottom', where standards are lowered to gain more access to minerals, the global standards must be kept high, especially as mining activities increase globally. The ICMM and IRMA standards are important steps in the right direction for better governance and management of facilities.

There is no free lunch for a more sustainable future. Higher standards for mineral extraction and processing will entail higher costs, and thus higher prices. Markets will react to these through innovation and the development of lower-cost substitutes. Future generations of low-carbon technologies may utilize fewer minerals and metals than current products, but governments will also need to regulate mining activities, incentivizing innovation, and penalizing any negative impacts.

The second step is boosting recycling, which could solve several problems. Once produced, minerals would remain in circulation, lessening the demand for primary extraction. Domestic recycling would also lessen import dependence, providing greater economic security and decreasing geopolitical risks. Most importantly, recycled metals and minerals would significantly reduce the environmental footprint of global mining activities, replacing them instead with recycling plants supplied by renewable energy.

It is also important to ask how we might find ways to significantly reduce global demand for critical minerals. If each internal combustion engine vehicle is replaced by an EV, the demand for minerals will skyrocket because every new EV that rolls off the sales lot contains large quantities of critical metals. Subsidizing EV ownership, as many governments are keenly doing, assumes that the only feasible replacement for conventional cars is a one-to-one swap for EVs. Better public transportation options and improved infrastructure for micro-mobility (including e-bikes and e-scooters) may lessen the demand for individual vehicle ownership. Ubiquitous EV charging infrastructure may reduce the need for large battery packs in EVs. Stationary battery systems used in electricity storage applications, where weight and size are less important than cost, may rely on metals and minerals that are more abundant and less critical.

Governments have a significant role to play in all of this. First, boosting research and development for cleaner mining technologies will lower the environmental footprint through innovation. Second, developing and supporting recycling infrastructure will lessen resource dependence. Third, transparency and recycling mandates can build a system of closed-loop responsible use. And fourth, consultation and accommodation of local and Indigenous communities affected by mining activities can mitigate and avoid social harm, while fostering local economic development and land sovereignty. Because of the global nature of mining and related international trade, governments also need to collaborate to develop global standards and protocols that will support transparency while reducing social and environmental impacts. With determination and creativity, we can create a sustainable path forward.

Endnotes

1 See also 'Where We Find Metals' by Shaun Barker in this volume.

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3 See also 'The Face of Mining' by Carol Liao in this volume.

4 IEA, *The Role of Critical Minerals in Clean Energy Transitions* (Paris: International Energy Agency, 2021), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

5 Matthieu Favas, 'How to Avoid a Green-metals Crunch' (11 September 2023), *The Economist*, https://www.economist.com/finance-and-economics/2023/09/11/how-to-avoid-a-green-metals-crunch

6 US Geological Survey, *Mineral Commodity Summaries, 2022* (Reston, VA: US Geological Survey, 2022), https://doi.org/10.3133/mcs2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf

7 See also 'The Copper Supply Gap: Mining Bigger and Deeper' by Erik Eberhardt in this volume.

8 See also 'Can Small Mining be Beautiful?' by Marcello M. Veiga and J. Alejandro Delgado-Jimenez in this volume.

9 See also 'Metal and Water' by Nadja Kunz in this volume.

10 See also 'Mine Waste' by Roger Beckie in this volume.

11 Ibid.

12 See also 'A New life for Old Metals' by Maria Holuszko in this volume.

13 See also '*Black Panther* and an Afrofuturist Vision of Mining' by Sara Ghebremusse in this volume.

14 See also 'Colonialism and Mining' by Allan Edzerza and Dave Porter in this volume.

15 The British Columbia legislature turned UNDRIP into local law through the adoption of the Declaration on the Rights of Indigenous Peoples Act (DRIPA) in November 2019 (full text available at https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/19044). Yet, implementing DRIPA requires alignment with other statues. British Columbia's Mineral Tenure Act dates from the 1850s and has not been updated to reflect Indigenous rights (full text available at https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/00_96292_01).

In its current form, the Mineral Tenure Act permits mineral claims to be staked on lands of Indigenous communities without their knowledge and consent.

16 Global Tailings Review, *Global Industry Standard on Tailings Management* (2020), p. 4, https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf

17 Initiative for Responsible Mining Assurance, *IRMA Standard for Responsible Mining IRMA-STD-001* (2018), https://responsiblemining.net/wp-content/uploads/2018/07/IRMA_STANDARD_v.1.0_FINAL_2018-1.pdf