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ORIGINAL PAPER

Financing the responsible supply of energy transition minerals

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Abstract

A group of minerals has emerged in recent years as critical to low-carbon energy and other technologies. The extraction and processing of these minerals will have to increase substantially if countries' plans for transitioning away from fossil fuels are to be realised. This paper sets out the challenges posed by this projected expansion in mineral production, and how they need to be addressed if this expansion is to take place. One of the main challenges is the mobilisation of the necessary level of investment in the production of these minerals, which involves specific risks beyond the inherent risks of exploration and mine development, including uncertainty about future technological trajectories, the potential for conflict with host communities, the concentration of mineral processing in China, and extended and vulnerable supply chains. Risks of conflict can be reduced by 'responsible mining' that gives enhanced attention to the environmental, social and governance (ESG) issues raised by mining, and supply chains can be made more resilient, and the need for new mines reduced, by implementing circular economy strategies to keep mineral products in use for as long as possible. 'Sustainable finance' is an approach to investment with such considerations at its heart, but which may need a 'green premium' to be widely implemented. The paper explores all these issues in detail and ends with a series of recommendations for how the production of energy transition and other critical minerals can be secured at the required level in a sustainable and responsible way in the future.

Keywords Energy transition minerals · Responsible mining · Sustainable finance · Circular economy · Recycling

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Introduction

In October 2025 the UNEP International Resource Panel (IRP) published a report entitled *Financing the Responsible Mining of Energy Transition Minerals for Sustainable Development* (UNEP IRP, 2025). This paper updates the data and summarises the key insights from that report, while presenting them in an appropriate academic form.

Access to energy transition minerals (ETMs), and associated refining and processing, is fast becoming a fundamental requirement for both industrial and industrialising countries, with implications for defence, national security, digitalisation and AI, as well as pretty well everything to do with electrification and the energy system.

Multiple published scenarios indicate that the global efforts to reduce carbon-based greenhouse-gas emissions using technologies such as photovoltaics, windmills and battery-operated electric vehicles will considerably accelerate the future global demand for the wide range of minerals and metals required by these technologies (Watari et al. 2018, 2020; UNEP IRP, (2022 and 2025); Hund et al.

2020; Gielen 2021; Gielen and Lyons 2022), the International Energy Agency (IEA) 2021, 2023, 2024a and 2025a; Christmann et al. 2022; Marscheider-Weidemann et al. 2022; the US Department of Energy 2022; and The European Commission (2023a, 2025); the International Renewable Energy Agency (IRENA) and the Norwegian Institute for International Affairs (NUPI, 2024a, b). All point, with diverse intensities, to an important rise in the demand for primary minerals and metals, those extracted from geological resources.

Additional factors such as:

- Global demographic trends (UN DESA, 2024),
- The development of the world's middle-class (Kharas 2017; Caballero and Sampaio 2025),
- Technological innovation (Marscheider-Weidemann et al. 2022),
- Rising investments in the defence sector related to worsening global geopolitical fragmentation and competition (Girardi et al. 2023; Hackett et al. 2025).

will further stimulate the demand for the extraction of minerals and metals.

Section 2 explores the extent of the increase in ETMs that is likely to be required, the prospects for extracting this level of minerals and the investment that will be required, as well as the risks that will need to be successfully navigated for the scale of extraction that is entailed. This new mining will not necessarily be additional to the mining that is already being carried out, partly because much of the increase in production will come from extending existing mines, but also because, with the energy transition facilitated by ETMs, much of the substantially larger mining activity for coal will cease. Extending underground mines may also offer possibilities for new sustainable mining. Even so, the ETMs will require many new mines in new places, some of which will be socially and environmentally sensitive. 'Responsible mining' is the term that has emerged to describe mining that is more positively attuned to these issues than some mining in the past, and that dramatically reduces the environmental impacts of extraction and provides increased social and economic benefits for the communities and countries in which the new mining. This is the topic of Sect. 3.

Given the quantity of ETMs that will be required, it is essential that, once mined, they are kept in circulation and use for as long as possible. Section 4 discusses how ETMs can and must become part of a circular economy. Section 5 links the two themes in the report of the joint need for a great uplift in mining investment and for 'responsible mining' through the concept of 'sustainable finance'. Section 6 concludes with the recommendations that were made by UNEP IRP (2025), which provide an overview of the issues covered in this paper and the wider report, and embody a 'call to action'.

Investment requirements for energy transition minerals

The International Energy Agency (IEA, 2025a) estimates the demand over the 2024–2050 period for several minerals essential to the global transition towards the low-carbon energy production needed to reduce the emissions that are driving global climate change. The IEA's most minerals-demanding scenario, the Net-Zero Emissions scenario (NZE), estimates the following demand increases over 2024–2050, including for uses in other economic sectors than energy production, distribution and storage:

- Cobalt: + 101%.
- Copper: + 53%.
- Natural graphite: +794%.
- Lithium: +339%.
- Magnet rare earths (variable, technology-specific, amounts of neodymium, dysprosium, praseodymium and terbium): +148%.
- Nickel: +119%.

However, technological shifts, especially in the design of batteries for electric vehicles, could reduce the future demand for several current battery minerals and metals (Home 2025). The rapidly growing global market share of lithium-iron-phosphate batteries (LFP batteries), representing about 50% of the global 2024 battery sales for electric vehicles (International Energy Agency, 2025b), is putting downward pressure on demands for nickel and cobalt, which are not needed for making these batteries. Graphite-free anodes and even lithium-free sodium-ion batteries could become widely available at competitive prices within the next ten years. Technology shifts are black swans that add much uncertainty to any demand scenario for minerals and metals that tries to figure out demand trends beyond the next few years.

While every possible political, economic, and technological effort needs to be made to translate the circular economy concepts (UNEP IRP, 2020, 2025) into standard everyday political, industrial, and individual practices, major hurdles remain despite all the progress already made. This is particularly well-documented for the recycling of minerals and metals (Reuter et al., 2013; this paper's Sect. 4).

Meeting the future demand for minerals and metals will require massive investment (UNEP IRP, 2025) in the following areas, notwithstanding the many uncertainties about

future development pathways, and the strong interactions between technological innovation and geopolitical issues.

- The development of public digital geoscientific data infrastructure, and of derived information, a key component of the mandate of publicly-funded Geological Surveys, is needed to guide later investment in the exploration of potential mineral deposits. According to a World Bank study (Halland et al. 2015), the investment needed varies from USD 10 to 100 per km2 covered, depending on factors such as the scale (or resolution) of the data acquisition, and on the technologies used. Additional efforts needed to identify specific targets require USD 0.5 to 2 million per target.
- A staged approach of mineral exploration activities is used by investors to manage mineral exploration risks, only funding the subsequent stage if the outcomes of the previous one justify the new, higher, investment in the subsequent stage. If economically justified, exploration activities conclude with the demonstration of the economic feasibility and, hopefully, of the environmental and social sustainability of the deposit's exploitation. According to Hund et al. (2020), depending on the size and complexity of the exploration target, and of the work needed to complete a professional standard feasibility assessment, the investment required can be as much as USD 60 million for the largest and/or most complex projects.
- If the outcomes of the feasibility study seem likely to provide economically attractive returns, the last, and by far the most important investment will be to finance the Initial Capital Expenditure (CAPEX) needed to build and commission the new production facility. So far, the largest initial CAPEX investment in the development of a new production site is the USD 22.7 billion investment in the Wa'ad Al Shamal phosphate mine and fertilizer plant in Saudi Arabia (Mining.com, 2025).

S&P Global Market Intelligence (2025) provides an estimate of the global investment, in nominal USD, in mineral exploration over the 1997–2024 period. After conversion of the data into constant 1998 USD using the US Consumer Price Index as deflator, to follow USGS practice for historical price data series, it shows (Fig. 1) a sharp decline in mineral exploration investment after the 2012 peak. The report also highlights the persistent dominance of investment in gold exploration (44% of the total 2024 estimate) and the record low observed in 2024 for grassroots exploration (22% of the total exploration budget), which looks for deposits in areas where none are mined so far, opening the possibility for new important discoveries.

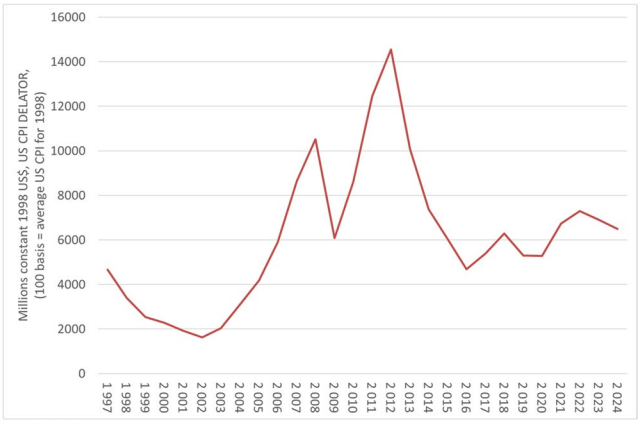

Fig. 1 Global annual mineral exploration investment estimate, in million constant USD (1998 value). Data source: S&P Global Market Intelligence, 2025

These trends do not bode well for the long-term supply of minerals and metals. They are aggravated by the rising cost of mineral exploration driven by the need to find deeper seated, concealed deposits or to explore in so far underexplored remote locations with poor or no infrastructure, and/or in locations that raise complex environmental, governance or social issues.

Schodde (2022), based on 2022 metal prices, estimated that, over the 2011–2022 period, the return per USD invested in global mineral exploration was, on average, only USD 0.64. This does not mean that investing in successful exploration activities cannot be highly profitable, but the average figure is likely to discourage many would-be investors.

In 2025, Schodde published a detailed, very informative, assessment of the key exploration trends over the 1900–2023 period, based on the analysis of a database of over 60,000 deposits worldwide, with over 13,000 considered as "significant" (from the economic point of view) on the basis of their documented resources (Schodde 2025). It provides a rare insight into exploration-related trends and issues.

On the basis of the data available from the 2025 edition of the annual Global Mining Project Spending Outlook (Govreau, 2025), average initial CAPEX requirements for new mining projects (with the number of projects in brackets) are given for the main categories of mineral raw materials, which include some mineral raw materials for the energy transition:

– Copper: USD 1912 million per project (72 projects),
– Lithium: USD 728 million per project (36 projects).
– Rare Earth Elements: USD 1432 million (7 projects).

These figures provide a measure of the levels of future investment needed in order to just meet the demand arising from the global energy transition.

In addition, unquantified but large-scale (multiple billions) investment will also be needed:

- To develop the human resource base needed to sustainably develop, operate, and manage (management by both the project/operations owners and the needed supervisory/regulatory authorities) the mineral- and metal-producing industries;
- To fund the research, innovation and scale-up activities needed to conceive processes, products and services faster, smarter and more sustainably;
- To develop and manage the multiple, complex, industrial supply chains that are needed to transform minerals and metals into the wide-range of products and services needed to achieve a low-carbon global economy.

In the 2024 edition of its Transition Metals Outlook, BloombergNEF (2024) estimates that 2.1 trillion USD in investment will be needed by the energy transition metals sectors between 2024 and 2050, to meet the demand resulting from a NZE transition.

Such investment is confronted by a wide-range of potential economic, governance, environmental, technological and social risks (see Annex to Chap. 5.5, UNEP IRP (2025)), that can dramatically affect the returns. These risks need to be identified during the exploration stage together, whenever possible, with their adequate mitigation strategies and their impacts on CAPEX and OPEX.

Energy transition investment risks.

The poor identification by project owners and/or supervisory governmental authorities of project-specific risks, insufficiently described and ineffectively implemented mitigation strategies, and the lack of transparency of a given project's potential environmental, social and governance (ESG) impacts, can badly affect a project's economic returns, and even lead to conflicts. Such issues can stall projects for years, sometimes decades, and in the worst cases result in chaos and fatalities. In December 2025, the Global Atlas of Environmental Justice[1] documented 839 conflicts related to the extraction of mineral ores and building materials, highlighting the limited progress made so far by the mining industry as a whole in properly addressing mining-related ESG issues.

Every year EY, one of the world's largest professional services networks, publishes a survey of the top 10 business risks and opportunities for mining and metals (latest edition: EY, 2025). The following connected risk categories were identified as key risks over the 2020–2025 period:

- Licence to operate: 2020, 2021.
- Environment and social: 2022.
- Environmental, social and governance: 2023, 2024.
- Capital: 2025.

In 2026 the top position in the EY ranking was occupied by Operational Complexity (see Fig. 2), but ESG risks remain at the heart of EY's "top ten risks" facing the mining industry, listed as Resource/reserve depletion, Licence to operate, and Sustainability.

In fact, ESG issues are progressively being translated into project financing issues, related to operational complexity, rising costs and productivity and capital, the top three issues for 2026. These are deterring the needed investment in future exploration and production.

Minerals and metals are standardized, internationally traded commodities meeting physical and chemical specifications. Therefore producers need to ensure that their production costs stay below the market price of their products. This makes it challenging for mining companies to address ESG issues whose management does not result in reduced production costs (see Sect. 5). While the reduction of chemical, energy and water inputs provides environmental benefits and a reduction of production costs, such benefits are much more complex to achieve in relation to biodiversity and waste management, given the very long-term legacies (centuries and more after the end of a given mine's activities) from past mining, ore processing, metallurgical, and refining activities.

The high and increasing technological importance of ETMs has been accentuated by the growing geopolitical tensions of recent years, and the extreme concentration of the extraction of some of these minerals and their refining and processing in China, as shown in Fig. 3.

Fig. 2 Top 10 business risks and opportunities for mining and metals in 2026. (EY, 2025)

[1] https://ejatlas.org/.

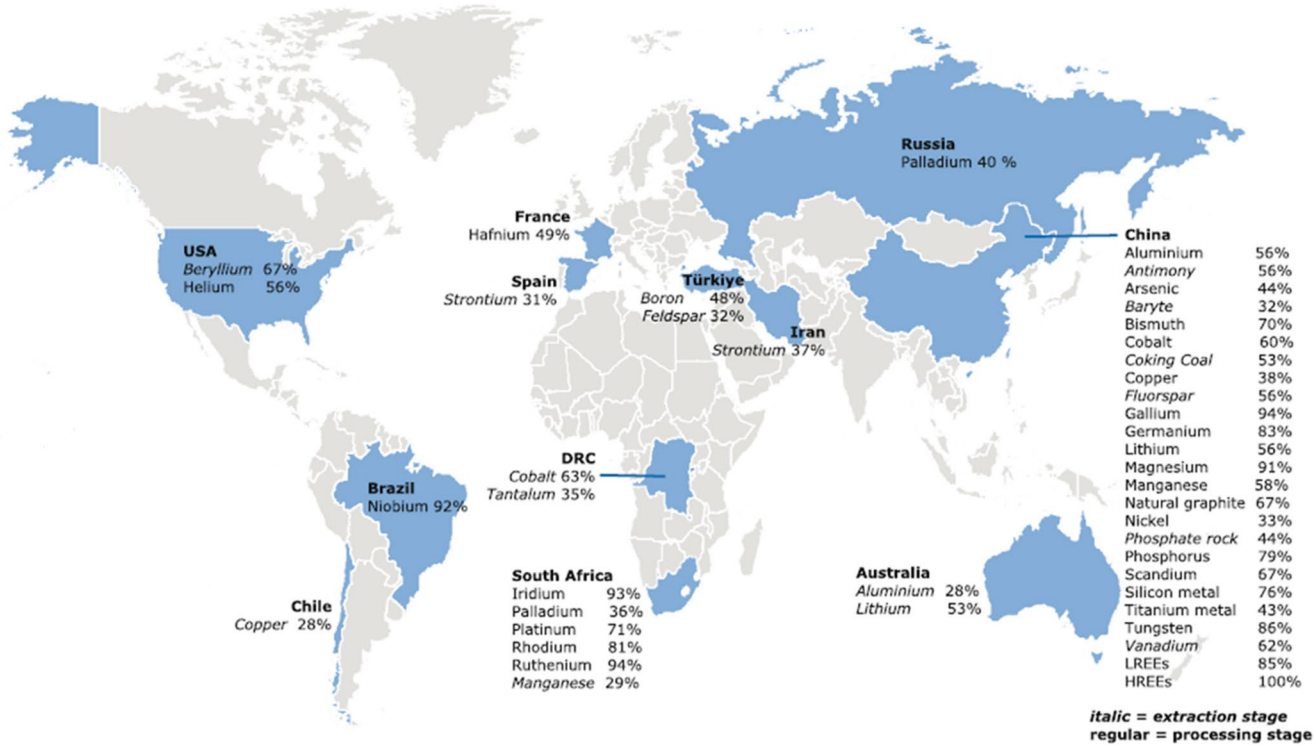

Fig. 3 Countries with the largest share in global supply (extraction and processing) of European critical raw materials (CRMs). Source: European Commission (2023a), Figure B, p.7

Many countries have developed critical mineral, or critical raw material, strategies, in order to try to secure their supply chains of these minerals. This will be no easy task given the levels of investment that will be required in both extraction and processing for countries to diversify their sources of these minerals away from reliance on countries with currently near-monopolistic levels of global production. The increasing salience of this issue is reflected in EY's annual mining industry risk assessments over the 2020–2025 period, in which geopolitics appeared as a risk factor in 2021, then in the 5th position and now (EY, 2025) in the 3rd position.

The already low investment level in mineral exploration and mining, much of which is financed through the retained profits of multinational mining companies, could be aggravated in the coming years as a consequence of growing, already very high levels of public debt in many industrial countries. There is a probability that to fund their rising public debt, in a chaotic, fragmented, global economy, States will have to raise the interest rates they offer on their treasury bonds, with the US government 10-year Treasury Bonds (T-Bonds) being so far the global standard for "risk-free" investment. On February 12, 2026, their yield was about 4.1%, meaning that investment in risky mining projects should reward investors with a significantly higher return on investment. Despite attractive economic metrics documented in published feasibility studies projects may struggle to attract the initial capital (CAPEX) funding needed to turn exploration findings into producing mines. For example, even some copper production projects with published feasibility studies completed 10 years and more ago are still waiting for a final investment decision, for example Copper Schaft in British Columbia, Canada (2013 was the publication year of the initial feasibility report), Gunnison in Arizona, USA (2016 was the publication year of the initial feasibility report). Even more projects struggle due one or several, frequently interacting factors. These factors include regulatory uncertainty, governance issues, local conflicts, and environmental and/or social concerns.

This does not bode well for the future availability of all the minerals and metals needed, inter alia, to achieve the global transition towards a Net Zero Carbon economy.

Conclusion

The technologies that depend on valuable minerals and metals provide humanity with a remarkable opportunity to address some of the challenges facing humanity, such as climate change.

Reaping the benefits of these minerals and metals requires well-coordinated, funded, global action to develop an enabling framework of common rules, based on transparent

economic, environmental, social and governance metrics specific to each significant mineral and metal project, and on integrating environmental and social concerns into the pricing of minerals and metals. Creating such a framework will require knowledge-based dialogue among the multiple stakeholders that have a role in mining projects, or are impacted by them. The responsible mining that needs to emerge from such dialogue could accelerate projects while reducing conflicts and building trust. Such mining is the subject of the next section.

Responsible mining

Definitions and concepts

'Responsible mining' is a concept arising from the 1990s' concern with corporate social responsibility, and was initially spearheaded by the project Minerals and Mining for Sustainable Development (MMSD) (1998–2002), which led to the formation of the International Council on Mining and Metals (ICMM) and the signing of the Toronto Declaration (Danielson 2022). There is now a renewed emphasis on this concept among mining companies, and among the financial institutions that invest in them.[2]

The deep interconnections between ESG factors, human rights, societal resilience, and business and investment viability make it essential not to consider such issues as a "tick box" exercise. Similar criticism has been aimed at the so-called "licence to operate", with corporations often delegating to third parties the reduction of environmental and social risks to local communities, instead of making these issues "core business" (Owen and Kemp 2013) (Hopkins and Kemp 2021). Such criticisms have also led to proposals for a more comprehensive and systems-based "sustainable development licence to operate" (SDLO).

Failing to manage ESG risks is one of the major causes of opposition to mining, and of conflicts involving local communities where mines are operating, as discussed in Sect. 2.

According to the International Resource Panel (IRP) of the United Nations Environment Programme (UNEP) "the responsible production of minerals and metals can be defined by the industrial and institutional rules, procedures and operational practice that align, at the level of individual production sites, to meet society's needs for minerals and metals, ensuring economic returns for investors and enterprises without causing unsustainable environmental and social harm as a result of production activities or their legacies after the end of such activities." (UNEP IRP, 2025, p.ix) This makes clear that responsible mining should cover ESG issues through the whole mining life-cycle, from exploration through to mine closure and land remediation.

Mining is an extractive industry with particular land use dynamics requiring meticulous management of ESG issues, due to its evolving footprint over the mine life cycle. Major concerns include the environmental and social risks of mine tailings, context-specific land tenure agreements, and displacement and resettlement. After initial exploration, mine operation can take months or decades to begin, and can be paused at virtually any moment with no guarantee of restart, proper closure, or retention of the same owners and operators. The mine life cycle creates vastly different experiences for stakeholders, including employees, local authorities, national governments, local residents, and indigenous communities, as well as for the mining companies themselves (Lèbre et al., 2020).

Public scrutiny has increased following catastrophic tailing dam collapse events in 2015 at Mariana[3] and in 2019 at Brumadinho[4] (Rotta et al. 2020) which led to extreme environmental and social impacts and the death of over 270 employees and local residents, as well as adverse outcomes such as the destruction by Rio Tinto in 2020 of indigenous archaeological heritage at Juukan Gorge[5,6] (Hopkins and Kemp 2021).

Standards and assessment

In an attempt to reduce complexity and introduce more clarity in the standards landscape, the ICMM announced the Consolidated Mining Standard Initiative (CMSI)[7] in 2024. This covers ethical business practices; worker and social safeguards; social performance; and environmental stewardship, and brings together the standards of The Copper Mark, the Towards Sustainable Mining (TSM) initiative of the Mining Association of Canada, the World Gold Council's Responsible Gold Mining Principles and ICMM's Mining Principles.

The Responsible Mining Foundation emerged in the 2020s for assessing responsibility in mining and created the respected Responsible Mining Index (RMI). The Index scores companies for Commitment, Action and Effectiveness across six thematic areas (Economic Development, Business Conduct, Lifecycle Management, Community Wellbeing, Working Conditions and Environmental Responsibility), and four transversal issues (Human Rights, Gender, Open Data, and the Mine Site). (Responsible Mining

[2] https://www.icmm.com/en-gb/mining-metals/responsible-mining. Accessed March 3, 2026.

[3] https://en.wikipedia.org/wiki/Mariana_dam_disaster.

[4] https://en.wikipedia.org/wiki/Brumadinho_dam_disaster.

[5] https://www.riotinto.com/en/news/trending-topics/juukan-gorge.

[6] https://en.wikipedia.org/wiki/Juukan_Gorge.

[7] https://miningstandardinitiative.org/.

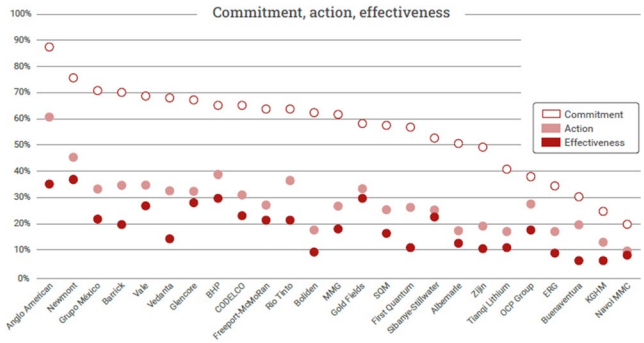

Fig. 4 Commitment, action and effectiveness scores in the 2025 report on the RMI (World Resources Forum Association, 2025)

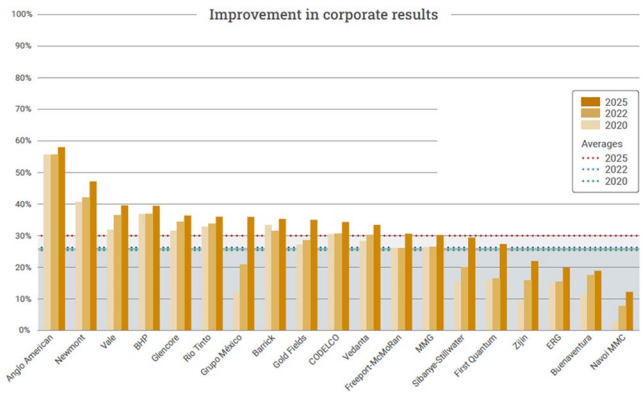

Fig. 5 Improvement in corporate results across the three published RMI reports (World Resources Forum Association, 2025)

Foundation, 2020, 2022). RMI reports were produced in 2020, 2022 and 2025, with the 2022 report assessing the performance across these issues of around 40 companies. The latest report in 2025, produced by the World Resources Forum Association, finds that the overall performance of the companies studied in 2022 only marginally improved, with concerns that the transparency of ESG policies and practices remains "strikingly low"[8].

Figure 4 shows the range of scores across Commitment, Action and Effectiveness across the companies in the 2025 report.

Figure 5 shows the improvement in corporate results across the three published RMI reports. Improvement is shown for all the companies, with the improvements across some of the companies that scored lowest in 2022 being quite dramatic, with Grupo Mexico being the stand-out example of this, increasing its score from just over 10% to 2022 to well over 30% in 2025.

The leader in mine site assessment on ESG issues is currently the Initiative for Responsible Mining Assurance (IRMA). It provides detailed and auditable requirements across the thematic areas of Business Integrity, Planning for Positive Legacies, Social Responsibility and Environmental Responsibility, where IRMA acts as an independent third-party auditor[9]. At the time of writing, 26 mine sites across the world had been or were being independently assessed (audited) against the IRMA Standard,[10] with the completed audits are published on the IRMA website, showing that mining site assurance is still very much in its infancy.

Artisanal and small-scale mining

Advancing ESG performance and responsible mining in artisanal and small-scale mining (ASM) can reduce supply chain risks for investors and improve the lives of miners and their communities. An estimated 45 million people are employed in ASM, with 100 to 150 million people globally relying on this income indirectly (World Bank, 2024; Tingini and Eniowo, 2025). ASM is labour-intensive, with low levels of mechanization and recovery (Hilson et al. 2018), generally carried out by individuals or in small groups with low levels of capital investment (UNEP IRP, 2020).

Despite making a large contribution to the supply chains of global ETMs (18 to 30% of global cobalt supply), ASM miners are marginalised and benefit very little from the sale of their products on international markets (World Bank, 2020) (OECD, 2019). Yet, ASM is increasingly recognised for its role in rural employment and as a poverty buffer, and for its potential to contribute to wealth creation, economic development and the SDGs (Fisher et al. 2009) (Verbrugge 2016) (Franks et al. 2023). Realising this potential and increasing the incomes and improving the working conditions of miners in ASM is likely to require some kind of integration of ASM and large-scale mining (LSM), together with 'formalisation' of ASM, which International Institute for Sustainable Development (IISD) (2018) defines as to "bring it into the formal sector through legal, regulatory and policy frameworks". IISD, 2018, identifies six important factors for achieving formalisation effectively. Integrating ASM and LSM prior and during formalisation rather than only focusing on formalisation can better and more flexibly address power imbalances between actors, context-based needs, land tenures, access to finance, etc. This section concentrates on access to finance.

Expanding access to finance for miners is critical to ASM's integration into the formal economy and increase in operational sustainability. The informal nature of ASM, combined with the financial institutions' perception of the

[8] https://www.wrforum.org/responsible-mining-index/.

[9] https://responsiblemining.net/what-we-do/assessment/#:~:text=It%20is%20the%20mine%20site,engagement%20in%20the%20assessment%20process.

[10] https://connections.responsiblemining.net/independently-assessing-mines. Accessed November 30, 2025.

sector as high-risk, has limited miners' ability to secure formal financing (Eniowo et al. 2022). Potential formal financing options range from debt instruments—such as microfinance, local savings and credit schemes, commercial banks, donor-supported programs, cooperative banks, government loans, and national development banks—to equity-based arrangements (UNEP IRP, 2025, p.265).

Many women are involved in ASM and they often experience even more institutional, normative and structural barriers to participate successfully in markets (Djoudi et al. 2016). Over one million children are estimated to work in ASM, a number that is growing [(Schipper et al. 2015), which is a major ESG concern. However, many women work with their children, and ASM revenue sometimes allow them to go to school and stay with their families. Therefore, well-thought out transition mechanisms that empower children and their families are essential, as they might otherwise be driven into greater risks and more dangerous activities, including engagement with criminal gangs (O'Driscoll 2017; Faber et al. 2017).

Operations financed by organized crime pose particular ESG and security concerns, and a number of schemes have been developed to ensure commodities are not linked to armed groups (World Bank, 2024). Some of these schemes have been criticised for their top-down structures and disregard for local dynamics and marginalized community members. An excessive focus on conflict-free supply chains has been found to primarily protect corporate public image interests (Radley and Vogel 2015).

The ASM community has articulated a vision for the future represented by the Mosi-oa-Tunya Declaration on Artisanal and Small-scale Mining, Quarrying and Development (Franks et al. 2020). This and the United Nations Environment Assembly Resolution on Mineral Resource Governance (UNEP/EA.4/Res.19) aim to mitigate supply chain risks for commodity buyers while enhancing the well-being of affected communities.

Building on recommendations from prior international policy frameworks, the ASM sector would benefit from an international mechanism addressing financial constraints. The Meridian Principles, modelled on the Equator Principles, has been proposed to improve conditions for miners and their communities while mitigating ESG risks in ASM operations (UNEP IRP, 2025, p.273).

Conclusion

All mining has potentially serious economic, social and environmental implications for the local communities and host countries in which the mining is being carried out. The concept of 'responsible mining' has been developed to increase awareness of these issues, and encourage mining companies to pay attention to, and publicly report on, them so that all stakeholders, particularly those in the affected countries and communities benefit from the increased mining of ETMs that is in prospect. While so far it has been the larger mining companies that have been under the responsible mining spotlight, it is just as important that these considerations are highlighted for the artisanal and small-scale mining sector, the workers in which are more numerous and generally face worse conditions than those in large-scale mining companies.

Of course, the number of new mines that will be needed to meet a given level of demand for energy transition minerals will be reduced to the extent that circular economy principles are applied to the products that contain these minerals, such that these products last longer in first use, and can easily be repaired, refurbished or remanufactured as required. Moreover, the products need to have been designed not only to permit this, but also for their constituent materials to be easily recovered and the minerals recycled into other uses at end-of-life. This is the subject of the next section of the paper.

Circularity in energy transition minerals

The circular economy aims to keep materials within productive use for as long as possible through design improvements, product sharing and end-of-life recovery. In respect of products that contain ETMs, circular approaches such as reducing, reusing, repairing and remanufacturing extend the lifespan of products and reduce demand for virgin materials (UNEP IRP, 2018), while recycling targets promote the reintroduction of end-of-life materials into the raw material stock (European Commission, 2023b; Graedel et al. 2011). These principles are exemplified in the electric vehicle sector, where remanufacturing batteries, repurposing components and recovering metals such as lithium, nickel and cobalt can substantially lessen supply risks and environmental impact (Cimprich et al. 2023).

However, whatever the lifespan of solar panels, wind power and electric vehicles, and whatever the subsequent uses of the materials that comprise them, at some point they will present as 'waste'. By 2050, discarded solar modules could amount to 60–78 million tonnes, while wind turbine waste may reach 43 million tonnes — figures comparable to projected global electronic waste from other sources (Ellen MacArthur Foundation, 2023; UNEP, 2019). In addition, spent electric vehicle and storage batteries are expected to reach a cumulative 1,300 GWh by 2040, highlighting both a challenge and an opportunity for material recovery and

reuse (International Energy Agency (IEA), 2021). 1,300 GWh amounts to 5–9 million tonnes of spent battery packs[11].

While recycling sits lower in the hierarchy of circularity practices than keeping materials in first use, it remains indispensable for maintaining the supply of essential transition minerals. It forms a cornerstone of the circular economy, and of efforts to decouple economic growth from the consumption of finite resources.

While the circular use of products containing ETMs is the main topic of this section, the issue of circularity within the mining industry is also a very important subject; beyond the circularity of mining waste (the issue of tailings is discussed below), it also entails the waste from production tools, such as the tyres of trucks and broken pieces of mills, as well. Progress in this area is very challenging and slow. But there are cases where circular practices are being adopted within mining operations. For example, Born (2025) contains an interesting case study about such practices in Chile.

Socio-technical and financial challenges of recycling of metals

Despite this potential, the recycling of ETMs faces major structural and technological barriers. A number of market uncertainties surrounding both mineral prices and technological pathways make investors hesitant to commit to long-term recycling infrastructure. Technology shifts may also reduce or change the composition of end-of-life products. For example, will the batteries in electrical vehicles, still require cobalt, nickel, or even lithium in 25 years from now? This is far from being certain.

In addition, the longevity of low-carbon technologies delays the availability of large quantities of recyclable material until at least the 2040 s (Christmann and Lefebvre 2022; Simas et al. 2022). Efficiency-oriented product design of low-carbon technologies often neglects end-of-life recyclability processes such as disassembly or material separation, while increased product complexity (especially in multi-component devices like batteries and wind turbines) renders efficient recovery difficult (Graedel et al. 2011; Lander et al. 2021). Outdated recycling infrastructure compounds these challenges and the logistics of transporting end-of-life products across borders remain fragmented. Even when recycling occurs, variations in pre-processing streams and lack of harmonised performance indicators make it hard to track outcomes or benchmark quality (Henckens and Worrell 2020; Reuter et al. 2013; van Schaik and Reuter 2014).

[11] Assuming a representative pack-level energy intensity of 150 and 200 Wh per kilogram (Arthur 2023; Browmick 2023; International Energy Agency, 2024b); Kane 2021).

Social and environmental factors further complicate the picture. The recycling of critical minerals requires strict environmental and safety regulations. This is important because handling materials like lithium can pose hazards, such as the risk of destructive fires during the recycling process, as seen in Scotland (BBC News, 2025) and South Korea (Hoskins 2025). Informal recycling sectors, prevalent in low- and middle-income countries, handle large volumes of e-waste but often operate without environmental safeguards or worker protections (Dias 2012; Nguyen-Tien et al. 2022; Schluep 2014). Informal operators play a crucial role in resource recovery yet are exposed to hazardous conditions and receive little financial support. Formalising these systems while retaining their economic value is essential for equitable circularity (Reuter et al. 2013). Public awareness is another missing link: without consumer engagement and proper waste segregation, even the most advanced recycling facilities cannot reach optimal recovery rates (Prestin and Pearce 2010).

Financing is a decisive bottleneck. The economics of recycling remain fragile due to high upfront costs, uncertain feedstock availability and volatile secondary material prices. At present, the disparity in fiscal and policy support between primary mining and secondary production distorts incentives. Primary production benefits from subsidies, tax breaks and infrastructure investments, whereas recyclers face limited access to capital and inconsistent policy frameworks (McCarthy and Börkey 2018). Redirecting financial instruments to create parity between virgin and recycled materials could significantly strengthen the business case for circularity.

Public and private finance can help alleviate these challenges

There is much that governments and international financial institutions can do to address the challenges of recycling as well as the imbalance between primary and secondary production. These include the issuance of green bonds, sustainability-linked (concessional) loans, and the promotion of impact investment and blended finance models that de-risk private investment and lower the cost of capital for recycling ventures (UNECE, 2023; UNEP FI, 2020). Blending public and private finance to support high-risk demonstration projects would enable the commercial scaling of novel recycling processes, including hydrometallurgical and bioleaching techniques for ETMs. Targeted fiscal reforms (such as reduced tariffs on recycling equipment or preferential access to public procurement for recycled materials) could accelerate technology diffusion. Public–private partnerships (PPPs) could help expand collection networks, upgrade processing technologies and integrate digital traceability

systems. Governments can encourage private participation through tax credits for recycled inputs, extended producer responsibility (EPR) schemes and dedicated funds for recycling research and development. In parallel, setting measurable targets for recycling rates and secondary material shares is crucial. Reliable, standardised data would enable transparent reporting and accountability, attracting further capital and policy attention.

Some governments have already begun to address the need for circular economy finance. The United States has invested around US$125 million in research and development for circular battery systems, while the European Investment Bank has pledged €1 billion to the European Battery Alliance to boost battery manufacturing and recycling (European Investment Bank 2020; US Department of Energy, 2022). These initiatives complement the European Union's Circular Economy Action Plan, which promotes improved product design, reuse and mandatory recycled content. However, global disparities persist, as most large-scale recycling initiatives are concentrated in high-income economies, leaving developing regions (often suppliers of primary minerals) without adequate recycling infrastructure or access to green finance.

A global database on tailings and waste stocks could unlock another underutilised opportunity. Hundreds of millions of tonnes of mine tailings hold substantial quantities of recoverable metals — secondary deposits that, with appropriate processing technologies, could provide economically viable and environmentally responsible supply (Reuter et al. 2013). Characterising these resources, mapping ownership and assessing recovery costs are preconditions for attracting investors and ensuring responsible re-mining.

Recent policy and industry developments in the EU and USA suggest that the governance and economic valorisation of tailings are already moving from conceptual proposals towards implementation. In the US, federal initiatives led by the U.S. Geological Survey are actively assessing critical mineral recovery from mine waste across multiple states, while pilot projects and regulatory adjustments aim to incentivise reprocessing (GLOBSEC, 2023). Similarly, in Europe, policy debates increasingly emphasise integrating re-mining into revised extractive waste frameworks to enable circular resource use and reduce primary extraction, alongside publicly funded projects such as NEMO that support metal recovery from residues (Transport & Environment, 2023). These efforts unfold within a broader shift towards stricter governance and transparency, exemplified by the Global Industry Standard on Tailings Management and emerging 'Tailings 4.0' approaches that combine digital monitoring, environmental safeguards and resource recovery strategies (Global Tailings Review, 2020). Taken together, this indicates that while large-scale reprocessing remains limited in practice, the institutional, regulatory and technological foundations for re-mining tailings are now actively being established, reinforcing the economic potential highlighted in the literature (Action Canada 2025; Manaviparast et al. 2024).

Innovative approaches to metals circularity include modifying mineral processing so that part of the crushed ore is turned into a clean, low-carbon manufactured sand – OreSand – before it becomes tailings, thereby reducing the volume requiring long-term storage and lowering associated environmental and safety risks (Sustainable Minerals Institute, n.d.). Developed through the University of Queensland's Global Centre for Mineral Security, OreSand is a circular economy approach that reframes mine waste prevention at source as part of more sustainable extraction, while also addressing rising pressure on natural sand resources used in construction (Sustainable Minerals Institute, n.d.; UN-Habitat 2024).

Conclusion

Achieving sustainable recycling demands recognition of the sector's social and environmental externalities. Poorly regulated operations can result in hazardous emissions, water contamination and exposure to toxic materials. Socially inclusive models (where workers receive training, health protection and fair wages) are essential for aligning responsible material recovery with responsible mining. PPPs can play a catalytic role here: governments can provide the regulatory framework and incentives, while industry and investors bring technological know-how and capital.

Recycling cannot completely replace mining but must complement it as part of a balanced strategy for resource security and sustainability. A robust circular economy in ETMs will reduce dependence on volatile primary markets, mitigate environmental damage and enhance the resilience of supply chains. By aligning financial systems, technological innovation and social inclusion, recycling can transform the production of secondary materials from a peripheral waste-management activity into a central pillar of sustainable industrial policy and climate strategy.

Sustainable finance and the need for a green premium

The two themes of the need for substantial investment in mining for ETMs, and the need for this investment to lead to 'responsible mining' that takes account of social and environmental, as well as economic, issues, have run throughout this paper. These two themes come together in the concept of 'sustainable finance', which has emerged as a central

pillar in global efforts to reconcile economic development with environmental protection and social inclusion. Initially rooted in ethical and responsible investment movements, it has evolved into a comprehensive financial paradigm that integrates environmental, social, and governance (ESG) considerations into financial decision-making. This evolution is particularly relevant in the context of the global energy transition, where, as has been seen, the demand for minerals essential for renewable energy technologies is rapidly increasing (International Energy Agency, 2021).

Sustainable finance finds its conceptual origins in sustainable investing, defined as an "approach that considers Environmental, Social and Governance (ESG) factors in portfolio selection and management" (European Commission, 2022, 2025). Sustainable investing encompasses a range of strategies through which investors incorporate non-financial considerations into capital allocation decisions (Lee and Suh 2022). These strategies include exclusionary screening, whereby certain sectors or activities are excluded due to incompatibility with ESG principles; best-in-class screening, which favours companies with superior ESG performance relative to sector peers; and norms-based screening aligned with internationally recognised standards (G20 Sustainable Finance Study Group, 2018). More integrated approaches involve embedding ESG metrics directly into financial analysis and valuation models, reflecting the growing recognition of sustainability-related risks and opportunities as financially material. Sustainability-oriented investments and impact investing go further by explicitly targeting positive environmental or social outcomes, often with measurable indicators and stakeholder engagement. Finally, corporate and shareholder action, also referred to as active ownership, uses investor influence to shape corporate behaviour and governance (Kumar et al. 2022).

Building on these strategies, sustainable finance can be defined more broadly as any form of financial service that systematically integrates ESG factors into business decisions. It encompasses a wide range of activities, including green and sustainability-linked bonds, sustainable investment funds, microfinance, active ownership practices, sustainability-linked credit mechanisms, risk assessment and disclosure, and compliance with evolving regulatory frameworks. Rather than representing a narrow subset of finance, sustainable finance constitutes an overarching framework that reshapes how financial actors perceive value, risk, and responsibility (Kumar et al. 2022).

Over the past decade, sustainable finance has expanded rapidly and become increasingly institutionalised within global financial markets (Widyawati 2020). This expansion is driven by two principal dynamics. First, many industries have undertaken "greening" efforts in response to climate change, resource scarcity, and reputational pressures. Second, investors, regulators, and civil society have heightened expectations regarding corporate accountability, transparency, and ESG performance (Ameli et al. 2024). Mandatory and voluntary sustainability reporting requirements are proliferating across jurisdictions, reinforcing ESG considerations as a standard component of corporate governance, reporting and disclosure (Spataru et al. 2024). Financial institutions increasingly treat climate change, social inequality, and governance failures as systemic risks that can affect asset values and portfolio stability. As a result, ESG integration has become a core element of fiduciary responsibility rather than a purely ethical consideration (Singh, Zhang and Anu, 2023). Public financial institutions and development banks have also played a critical role in mainstreaming sustainable finance by embedding ESG criteria into lending and investment decisions. At the corporate level, companies are increasingly adopting risk-aware management approaches that use sustainability performance to identify competitive advantages, access capital on more favourable terms, and maintain legitimacy in the eyes of investors and society. Consequently, sustainable finance now affects firms of all sizes, from multinational corporations issuing green bonds to small and medium-sized enterprises accessing sustainability-linked loans.

Despite its growing prominence, sustainable finance faces significant conceptual, political, and practical challenges (Agnew et al. 2022). One of the most notable recent developments is the backlash against ESG, particularly in certain political contexts, such as the US at present, where it is framed as ideologically driven or incompatible with market efficiency (Agnew et al. 2022). Critics argue that ESG metrics lack standardisation, rely on subjective assessments, and may enable greenwashing by allowing firms to overstate sustainability credentials without delivering substantive change (Financial Times, 2023).

This backlash has direct implications for sustainable finance. Regulatory fragmentation and political opposition can create uncertainty for investors and undermine long-term policy coherence (Larosa et al. 2022). High-profile cases, such as Northvolt (see below), involving sustainability-linked financial instruments have also exposed weaknesses in standards, monitoring, and enforcement, highlighting the need for clearer definitions and more robust verification mechanisms. Moreover, sustainable finance must grapple with inherent trade-offs in the green transition. While decarbonisation and electrification are essential for climate mitigation, they require substantial material inputs, intensifying pressures on natural resources and mining activities (Hund et al. 2020). These tensions underscore the limits of simplistic sustainability narratives and reinforce the need for credible, accountable financial frameworks. Mining critical minerals such as lithium, cobalt, and nickel often entails significant

environmental degradation and social risks, including biodiversity loss, water contamination, labour rights violations, and conflicts with local communities (Herrington 2021). In this context, sustainable finance has a crucial role to play in promoting responsible mining practices (UNEP IRP, 2025).

Public finance institutions are particularly influential in shaping sustainability outcomes in the mining and energy value chains. A salient example is the European Investment Bank's financing of a large-scale battery manufacturing project by Northvolt, amounting to over one billion US dollars (European Investment Bank, 2024). This investment reflects the strategic objective of supporting a European battery ecosystem aligned with climate goals while reducing reliance on unsustainable supply chains. At the same time, it illustrates the reputational and financial risks associated with large-scale green investments if upstream sourcing and mining practices are not adequately governed.

Sustainable finance can encourage responsible mining through several mechanisms. First, financing conditions can be linked explicitly to ESG performance, requiring mining and processing companies to comply with environmental safeguards, social standards, and governance requirements throughout exploration and development phases. Second, enhanced reporting and disclosure obligations improve transparency along mineral supply chains, enabling investors, regulators, and civil society to scrutinise impacts more effectively. Third, blended finance instruments combining public and private capital can reduce risks associated with investing in cleaner extraction technologies, and improved waste management and mine rehabilitation practices. Beyond formal conditionality, sustainable finance also shapes norms and expectations. When access to capital is contingent on adherence to internationally recognised ESG standards, companies are incentivised to engage more meaningfully with affected communities, conduct robust environmental impact assessments, and adopt long-term remediation strategies. In this sense, financial markets function as complementary governance mechanisms that reinforce, rather than replace, state regulation.

Finally, companies are proactively willing to adhere to sustainable extraction, processing, refining and smelting practices. Results from a global survey of large-scale companies (revenues larger than USD 50 million per year) reveal that respondents identify ESG factors as among the most critical for their business operations (UNEP IRP, 2025), identifying social (i.e., local community impacts and social licence to operate) and environmental (i.e., decarbonisation and water management) issues as significant in shaping strategic and operational decisions. Reporting is highly fragmented: out of 50 respondents, ESG information mostly consists of corporate-level quantitative data (22 responses) and qualitative assessments mostly using benchmarks (14 responses). However, when questioned about the implementation of ESG measurement frameworks, 20 companies reported that they currently assess ESG performance primarily at the operational or site level, subsequently aggregating these data to derive corporate-level metrics. While this approach reflects existing internal monitoring practices, respondents simultaneously acknowledged the growing need for harmonised and standardised measurement methodologies in order to engage effectively with external stakeholders—most notably pension funds, institutional investors, sustainability-linked funds, and impact-focused investment vehicles, which were consistently identified as top financing priorities for mining operators.

The findings from this survey indicate that responsible mining may incur higher costs than mining that does not meet higher ESG standards and may therefore be put at a price disadvantage in a market of undifferentiated commodities. This suggests that there is a need for the emergence of a 'green premium' for companies that demonstrably outperform their peers on ESG-related criteria. In this context, investors and sustainable finance frameworks have the potential to exert meaningful influence over practices across the mining value chain by differentiating capital allocation based on sustainability performance. While the magnitude and durability of such a green premium require further empirical investigation, preliminary evidence from the large-scale mining survey indicates that companies willing to increase operational expenditures to enhance the protection of human rights and broader social outcomes anticipate cost increases of approximately 51 to 75% relative to conventional, non-sustainable practices. In contrast, investments addressing environmental dimensions—including water management, soil protection, and biodiversity restoration—are associated with more moderate, though still substantial, increases in operational expenditures, estimated in the range of 25 to 50% (Fig. 6). Without the emergence of a 'green premium', and its validation by commodity markets, it is unlikely that many companies, and certainly not the industry as a whole, will feel able to adopt responsible mining practices to the extent required.

There is increasing recognition of the relevance of a green premium to more responsible or sustainable mining. Thus Gasimov et al. (2025) identify "the emergence of a green premium" as one of "six main levers for delivering change to sustainable operation" in mining. Azevedo et al. (2022) consider that "green premiums are emerging for several commodities and, in addition to factors such as pressure from inflation and the cost-of-living crisis, will increasingly shape the balance between supply and demand." While they do not identify the size of these premia, they estimate that these are most likely to be established for those commodities for which demand for 'green' products (interpreted by them

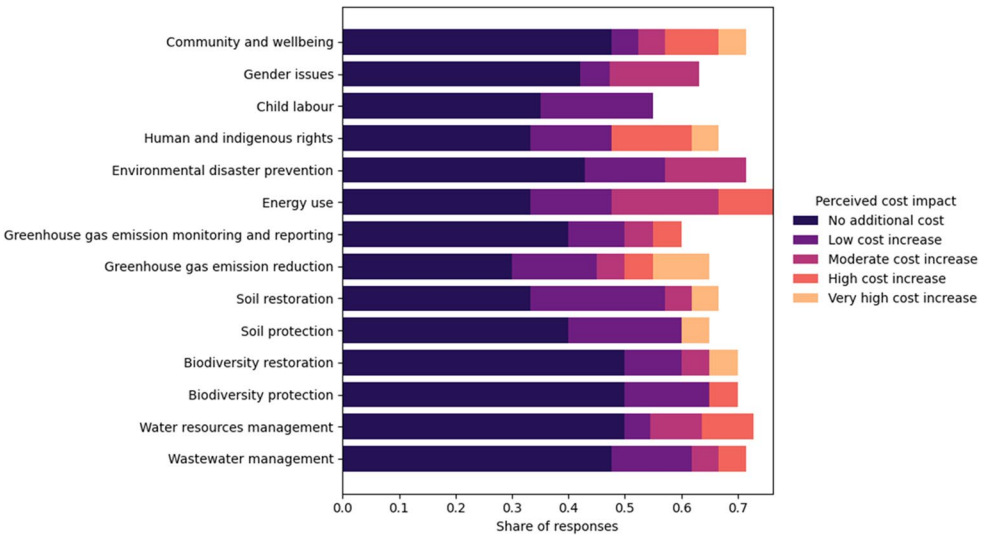

Fig. 6 Results from a survey of large-scale mining companies (UNEP IRP, 2025)

as 'low-carbon') is likely to exceed supply. Among metals, their analysis identifies steel and aluminium as likely to fall into this category.

The first actual identification of the size of green premia is being pursued by the London Metal Exchange (LME), as the result of a process that set in place its criteria for the Responsible Sourcing of metals in 2019[12]. LME has now set out a Roadmap for the identification of whether there is a price premium for sustainably produced (defined as below a carbon footprint threshold and conforming to a recognised standard [e.g. The Coppermark]) aluminium, copper, nickel and zinc, with a proposed extension of this list to cobalt, lead, and tin (London Metal Exchange, 2025).

Conclusion

Sustainable finance can play a pivotal role in shaping ESG practices within the mining sector. While companies increasingly recognise the strategic importance of ESG performance for accessing capital and managing social and environmental risks, current measurement practices remain fragmented, limiting comparability and weakening engagement with sustainability-oriented investors. The survey findings reported above indicate that harmonised ESG metrics are not merely a reporting requirement, but a prerequisite for unlocking potential financial incentives, including a prospective green premium for sustainability leaders. At the same time, the anticipated cost increases associated with enhanced social and environmental standards highlight the economic trade-offs that mining companies face in pursuing more responsible practices. These cost differentials reinforce the importance of sustainable finance mechanisms capable of offsetting or rewarding higher upfront expenditures through preferential financing terms, risk-sharing arrangements, or improved market access. Ultimately, the effectiveness of sustainable finance in promoting responsible mining will depend on its ability to translate ESG performance into tangible financial advantages, thereby aligning long-term investment incentives with environmental protection and social responsibility across the mining value chain.

Conclusions and recommendations

In free-market economies, investors show much less interest in minerals and metals exploration or production ventures than in investment in information and communication technology or in health-related companies. On December 18, 2025, the total market value of the world's 15 largest mineral- and metal-producing companies was about USD 1.3 trillion, and their average price/earnings ratio (PER) was about 23.2. Their market value was about 4.4% of the total market value of the world's 15 largest non-mineral and non-metal companies, a panel dominated by ICT and technology companies, with an average PER of 50.6, reflecting the greater attractiveness of the latter sector to investors. The total valuation of the top 15 global listed mineral and metal companies is at a level close to the world's 10th largest technology company, TSMC, a world-class Taiwanese microchip producer. And yet these minerals and metals are of fundamental importance to digitalization as well as to the energy transition.

The world needs to pay far greater attention to the availability, and to the sustainable and responsible exploitation, of Earth's natural resources. This brief paper has not been able to cover all the issues raised in UNEP IRP (2025), but the thrust of this coverage is summarised in the recommendations of the report, which fell into five related buckets.

[12] https://www.lme.com/sustainability-and-physical-markets/sustainability/responsible-sourcing. Accessed April 14, 2026.

1. Improve transparency, reporting and local engagement.

- Mining companies should report their financial, environmental, social and governance outcomes on a site-by-site, gendered and 'shared value' basis that also takes Indigenous rights into account, according to an agreed industry-wide protocol. Governments and stock-market supervisory authorities have a major role in this context.
- Site-by-site reporting on active mining or metallurgical operations should contain at a minimum the information covered by the International Resource Panel protocol for the planning and monitoring of mining operations (UNEP IRP, 2020).
- Current corporate processes that engage with and involve local communities in data acquisition and reporting should be developed and become more widely adopted.
- A digital product passport for all mineral commodities and their value chains, including environmental, social and governance-related information, should be developed on the basis of a standard reporting protocol, and be required by metal trading exchanges.

2. Incentivise higher mineral recovery and recycling rates as part of the circular economy.

- Incentives should encourage mining companies to extract high proportions of the metals in their ores.
- More information about tailings and other residues should be made available to open up possibilities for re-mining in the future.
- Exporting countries should benefit from the extraction of by-product metals recovered in the smelting and processing stages in other countries.
- The recycling of minerals and metals should be considered the final stage in circular materials management, following the application of other circularity approaches before products reach the end of their life.
- Policymakers should improve the economic viability of circular economy approaches to materials and product management by internalizing the social and environmental costs of primary materials production, implementing circular policies through the transition minerals value chains, validating novel financial instruments (e.g. green bonds) to increase investment in circularity, and supporting innovative remanufacturing and recycling technologies.
- In addition to the maximum use of circularity policies and approaches, material demand management is likely to be necessary to ensure that the material supply is sufficient for the essential uses in the low-carbon energy transition.

3. Improve the management of mineral markets and build stronger national institutions.

- Mineral-rich developing countries should be supported as necessary, through international development cooperation and other means, to legislate for and build the institutions needed to regulate responsible mining effectively and justly, so that the whole of society can benefit from the resulting mining boom.
- Jurisdictions that wish to actively stimulate mining to high environmental, social and governance standards and to import products from such mining should join together in a mining club for sustainable development and consider establishing a raw material border adjustment mechanism.

4. Reform the financial system: financial taxonomies, architecture and instruments.

- Mining that meets high environmental, social and governance standards should be included in the list of sectors in finance taxonomies (e.g. that of the European Union) that qualify for sustainable finance and should also qualify for a special form of climate finance. Concrete guiding principles on business and the environment – similar to the very effective United Nations Guiding Principles on Business and Human Rights – could enable responsible mining to be identified for this purpose.
- Reforms should be made to the financial system (e.g. taxonomies), governance (e.g. taxation regimes) and regulation (e.g. in terms of formalization of artisanal and small-scale mining) to ensure more capital flows to mineral exploration and mining for the clean energy transition, while ensuring the implementation of risk management and environmental, social and governance-related investment criteria.
- Mining investments and financing should be tied to mandatory climate and nature-positive requirements, subject to stringent audit requirements. In particular, mining should not take place in protected areas.
- Investors' financial portfolios with climate and biodiversity goals should be assessed and monitored for their alignment with defined and disclosed pathways to companies' alignment with climate and biodiversity goals. Financial institutions can use this to determine specific exclusion criteria and an engagement strategy that supports companies' transition pathways.
- Companies with transition plans that have robust validation should be able to receive sustainable and climate-related finance in order to signal their intentions to investors and financial institutions.

- Financial institutions should enhance their capacity to assess and manage the environmental and social risks and impacts associated with mining in order to be able to recognize and finance mining to high environmental, social and governance standards.
- Fiscal, financial and monetary policies should be used to support finance for and investment in responsible mining and infrastructure and for the more circular use of metals in society.
- The mining industry should implement a global 0.1 per cent ad valorem levy on all companies as a contribution to a mining sustainable development fund. In due course, this could become an internationally administered global sustainability tax, levied on all produced non-energy minerals and metals.

5. Establish international institutions.

- An international minerals and metals agency should be established to provide oversight and information about the state of and outlook for the world's non-energy mineral resources and markets. It should also provide support for capacity-building and institutional strengthening, especially in developing countries, as well as support for research and innovation activities and for the development of global minerals and metals exploration and production-related standards.
- The Network for Greening the Financial System should be encouraged undertake systematic monitoring of macroeconomic risks to the financial sector emanating from commodity markets, through a global commodity price observatory, eventually in collaboration with an international minerals and metals agency when one is created.
- An international framework for managing environmental and social risks and improving access to formal sources of finance in the artisanal and small-scale mining sector should be established.
- Governments, mining companies and NGOs should collaborate to establish a global database for mine tailings facilities and the potential availability of minor (or companion) metals, eventually to be managed by an international minerals and metals agency.
- In due course, a United Nations convention on sustainable resources should be established to encourage the sustainable production and consumption of resources, including resource efficiency and moves towards a circular economy.

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Data availability Data underlying Figure 1 is a compilation by the author of annual public reports. Over the years publishers and owners of the publisher varied. In 1991 and 1992 the survey was published by the Mining Journal; from 1993-2011mit was published by Metals Economic Group. The 2011 report is available at:https://www.mcilvainecompany.com/industryforecast/mining/overview/MEG%20Exploration%20trends.pdf . SP Global, has published these reports since. The data from these reports, which is nominal USD has been converted into 1998 constant US$ using the US CPI as a deflator.The data underlying Figure 6 may be obtained from the corresonding author.

Declarations

Competing interests The authors declare no competing interests.

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