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Research Briefing

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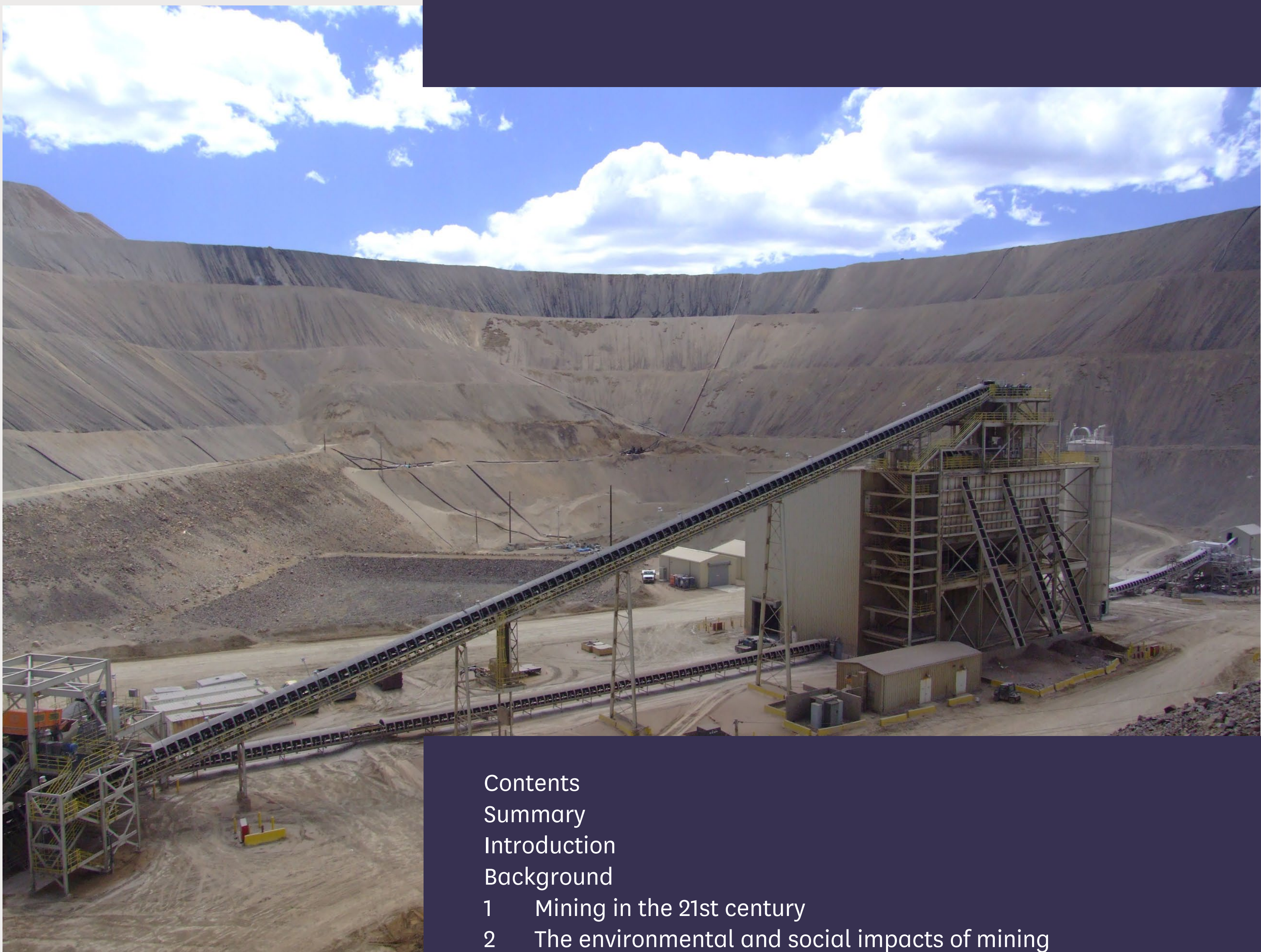
Mining and the sustainability of metals



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For further information on this subject, please contact the co-author, Dr Jonathan Wentworth.

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Summary

The transition of the world's economies and industries to more sustainable energy and technologies will require more mining and processing of non-renewable mineral resources, with associated positive and negative impacts on the environment and society.

The mining and processing of minerals underpins modern technology and infrastructure. Each year, over 3.3 billion tonnes of metals are produced globally,[1] and most predictions of demand show increasing consumption of metals in the coming decades, including in renewable energy generation, electric vehicles and batteries. The transition of the world's economies and industries to more sustainable energy and technologies will require more mining and processing of non-renewable mineral resources, with associated positive and negative impacts on the environment and society.

The UK is an important stakeholder in the modern mining industry. Although the UK production of metals is low, many of the world's largest mining companies are headquartered in the UK, investors and markets in the UK are a significant source of finance for the industry, and the London Metal Exchange is the largest market for the trade of metals. The oversight of mining, and the supply of mined materials (including metals and finished products that contain them) falls across several government departments, including DEFRA, BEIS, DIT and FCDO. The Government is drafting a UK Critical Minerals Strategy in 2022 as part of its Net Zero Strategy.[2] The UK imports ~40 million tonnes of metal year from a diverse global supply chain, that includes the EU (10%), China (12%) and South Africa (6%).[3] Trade and procurement are important mechanisms for the UK to secure responsible supplies of metals.

The Earth is likely to have sufficient metal ore deposits to meet projected demand over coming decades. However, there are concerns about the reliability of metal supplies. There is a general decline in the quality of ore deposits, in terms of the concentration of metals they contain, and an increase in the economic, environmental and social costs of mining them. Geopolitical threats to international supply chains, and long time frames (often a decade or more) in opening new mines means that metal supply could fail to meet rapidly changing demand. Ore deposits may occur in areas where mining would have unacceptable impacts on biodiversity, existing land use, and communities.

Although some individual mines are very large, overall less than 0.02% of the Earth's surface is used for mining (active and recently active mines).[4] However, the actual area used for mining is only part of a mine's true 'footprint', as the arrival of mining in wilderness areas allows other industries to follow, in some cases leading to wide-scale landscape change and biodiversity loss.[5] For example, mining is responsible for around 7% of annual forest loss in developing countries.[5,6] Air pollution, including acid rain, may have long distance, transnational impacts on biodiversity and forests.

Mines are governed by laws in the host countries. There is no global consensus on what should be permissible, and where, meaning that there is a very uneven legal landscape.

Mining and mineral processing consume large volumes of water, including in arid regions. The discharge of water from mine sites can result in serious contamination of waterways. The industry uses over 8% of the world's total energy each year to produce metals, and contributes to 10% of the annual greenhouse gas (GHG) emissions.[7] Improper storage of mine waste has resulted in humanitarian and ecological disasters.

Mining has a complex relationship with communities, culture and society in the countries in which it operates. Mining can bring employment, enhance services and infrastructure, and draw investment to the country. However, it is recognised as having the potential to create unequal societies, disproportionately affecting women, indigenous people and other marginalised groups. Mining operations can negatively impact on culture and heritage sites.

Artisanal and small-scale mining (ASM) can successfully support individuals to move out of poverty, although some activity – including illegal or illicit ASM – contributes to criminality, human rights abuses including child labour and modern slavery, money laundering, and the financing of wars. In the absence of effective governance, commercial, large-scale mining operations may also lead to criminality and human rights abuses. The value of mining to investors, governments and associated businesses means that petty and grand corruption surrounds mining. The UK has anti-corruption laws with overseas reach, and continues to work with partner countries to combat corruption.

Mines are governed by laws in the host countries. There is no global consensus on what should be permissible, and where, meaning that there is a very uneven legal landscape. However, there are a few areas in which international regulations place limits on the mining industry, particularly in terms of raising finance or accessing markets to sell products. These regulations have focused on fraud during initial financing, and human rights and criminality in supply chains, particularly for metals with significant artisanal production. The USA and EU both have legislation around conflict minerals; Northern Ireland is compliant with the EU regulations, and the FCDO expects the rest of the UK to align with the EU regulations and the OECD guidance from which they are derived.[8]

A wider suite of voluntary corporate sustainability reporting and certification schemes for environmental, social and governance (ESG) criteria have emerged in the last fifteen years, and are primarily to allow the commercial mining sector to demonstrate to investors that they are mining responsibly. The UK Government has given weight to some of these schemes, by enshrining participation for large companies in law – for example, beginning in 2022 over 1300 UK-based companies, including multinational miners, will need to disclose climate-related financial information on a mandatory basis – in line with the Task Force on Climate-Related Financial Disclosures (TCFD).[9] As much of the corporate ESG certification relates to the relationship between miners and shareholders or banks, private and state-owned companies (including those of China for example), may not be subject to the same scrutiny.

There are gaps in the transparency of reporting. The aggregation of data to company-level in sustainability reporting limits scrutiny, some metrics are under-reported, there is a lack of transparency and consistency on measurement methodologies.

The mining industry is taking steps to improve its environmental and social performance. However, there are gaps in the transparency of reporting. The aggregation of data to company-level in sustainability reporting limits scrutiny,[10] some metrics are under-reported,[11] there is a lack of transparency and consistency on measurement methodologies.[12] Innovation and best practice can help to mitigate some of the negative environmental and social impacts of mining, but the propagation across the industry is slow due to high capital costs, and competitive rather than collaborative efforts.

Recycling rates for many metals are low, and even if increased will not meet overall demand. For example, more than 50% of copper in end-of-life products is recycled, but this meets less than 25% of overall copper demand.[13] Our supply of metals remains dependent on mining. Reducing the consumption of metal through more efficient use, and offsetting more demand with recycling and reuse, will improve the overall sustainability of metal use.

Mining remains vital to the supply of metals, and will underpin a transition to more sustainable, low carbon energy and infrastructure. Better stewardship of metal resources, and more responsible mining operations can help to minimise the negative impacts on the environment and communities, and improve the overall sustainability of metal use. Although the UK mines little itself, it is home to some of the mining sector's largest companies, investors and markets, and Government policy has considerable influence on corporate transparency, environmental performance, and good governance.

Introduction

This POSTBrief uses the following structure:

- **Part 1** provides a brief overview of modern mining and metal supply, including the changing patterns of demand, the availability and 'criticality' of metals, the potential for recycling, and the UK's role in the global mining industry. Part 1 has an accompanying Annex to provide guidance on how the modern mining industry operates, including some of the essential technical steps in processing ore into metals.
- **Part 2** describes the major social and environmental impacts of mining and the potential to mitigate them. This section is subdivided into the main areas in which mining causes impacts –
  - land use and biodiversity;
  - water;
  - energy and greenhouse gas emissions;
  - air quality and non-GHG emissions;
  - waste including tailings; and
  - social, community and cultural factors.
- **Part 3** outlines the current governance structures around the mining industry, with particular emphasis on those that are relevant globally and to multinational corporations. Governance structures include regulations and legal frameworks, and voluntary or market-based reporting and certification schemes.
- **Part 4** provides a synopsis of how mining's impacts and governances relate, and discusses the industry's path towards more sustainable production, and in particular the challenges that will limit its ability to be truly sustainable at our current and predicted rates of consumption.

Background

Globally, mining can have major impacts on the environment and communities, both in the immediate vicinity of mining and processing sites, and more widely. It modifies the land surface, often permanently, with associated soil degradation, ecosystem and habitat destruction, and consequent loss of biodiversity

The mining and processing of mineral resources underpins the global economy and modern society. Each year, metals worth over £2,500 billion[1] are produced from the extraction and processing of ore deposits. Demand for metals and their products has increased steadily, driven by a growing population, industrialisation, GDP and consumerism.[14] The diversity of metals consumed has increased as a result of new technologies.[15] The growth of renewable energy supply has played a significant role in increasing demand and diversification, and will continue as the world's economies shift to lower carbon energy generation over the coming decades.[16]

Globally, mining can have major impacts on the environment and communities, both in the immediate vicinity of mining and processing sites, and more widely. It modifies the land surface, often permanently, with associated soil degradation, ecosystem and habitat destruction, and consequent loss of biodiversity. Mine waste storage facilities, including tailings dams, have failed, some resulting in loss of human life, and environmental impacts over a large area of land. Mining is a major source of CO_2 (4.8 billion tonnes of carbon dioxide equivalent (Gt CO_2) in 2015 – approximately 10% of the global annual total)[7]and other emissions such as sulphur dioxide, mercury and cadmium.[17] Mining and mineral processing are water intensive – the production of a tonne of copper may require 100 to 250 tonnes of water [18] – competing with other industries and communities for water in arid regions.

Mining and mineral processing activities can impact upon communities, and particularly those that live close to the sites. It may displace people (including indigenous groups), residences, and other industries including agriculture; and can be destructive to cultural and sacred heritage. Mining may foster corruption and inequality if governance is weak. In some cases, demand for mineral resources drives and supports armed conflicts and human rights abuses.

If done in a sustainable manner, mining can bring direct opportunities for development to communities in the form of infrastructure, education, employment and economic benefits among others.

Although mining can have negative environmental and social impacts, the global community depends on mineral resources for all modern industry, including 'green' technology and renewable power. With good governance, mineral resources can be transformed into economic wealth for host countries and communities, leading to income through taxation and royalties, employment, skills development and a resource base for other industrial sectors, including the green economy.

The mining industry has obligations to mitigate, reduce and avoid its social and environmental impacts. Mines are subject to regulation both in their countries of operation and internationally, and there is pressure from investors, consumers and markets to demonstrably reduce negative impacts. The public acceptability of mining, relationships with local communities, and NGO activity also play an important role in whether mining operations begin (or continue).

The environmental and social impacts of mining represent a risk for the mining industry – disasters, accidents, missteps and poor community relations may lead to reputational damage, legal action, closure of operations and loss of financial backing. Environmental change is a growing operational risk.[19] Mining is a large consumer of water, and increasing droughts and water scarcity will limit operations in arid areas. The increasing occurrence and severity of extreme weather events hampers production, and may cause deterioration in the stability of waste and tailings piles.[20]

The diverse range of stakeholders and participants in the mining and metal production supply chains make the monitoring, recording, tracking and auditing of environmental impacts and their mitigation a challenging task. Markets and consumers need verifiable data on mining and mineral processing impacts, so that they may make informed decisions.

1 Mining in the 21st century

1.1 Trends in demand

Historical demand and prices

The growth of renewable power – particularly when considering 'net zero carbon' ambitions – will move the world's economies from a fossil fuel basis to one of metals.

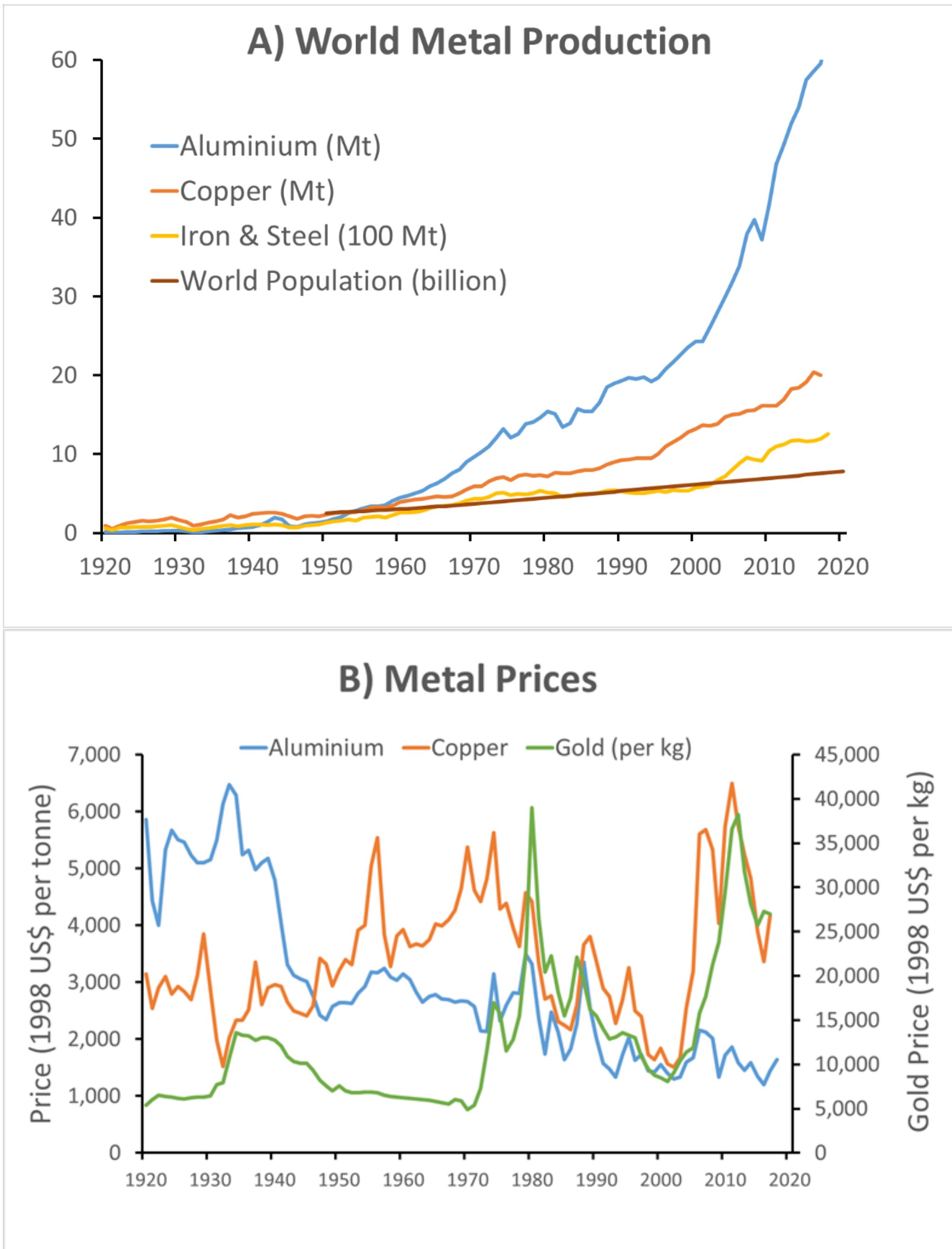
The demand for metals increased throughout the twentieth century, driven by a growing population, urbanisation, industrialisation, and increased per capita income.[21] When corrected for inflation, metal prices have fluctuated throughout the twentieth century, with relatively low prices through the late '80s and '90s.

In the early 2000s, the growth of economies, particularly China's, led to a boom in metal consumption (Figure 1A), with marked increases in per capita production of aluminium, steel and copper. This led to rapid price increases across a number of metals and particularly copper and gold (Figure 1B), and drove growth in exploration and mining. Increasing prices allowed miners to target poorer quality (higher cost) ore bodies. The Global Financial Crisis of 2007 onwards led to reduction in demand by China and other major consumers, putting many metals into periods of oversupply, depressing prices, and leading to poor financial conditions for the mining industry in general, with volatile metal prices, mine closures, and reduced exploration for new resources.

Future demand

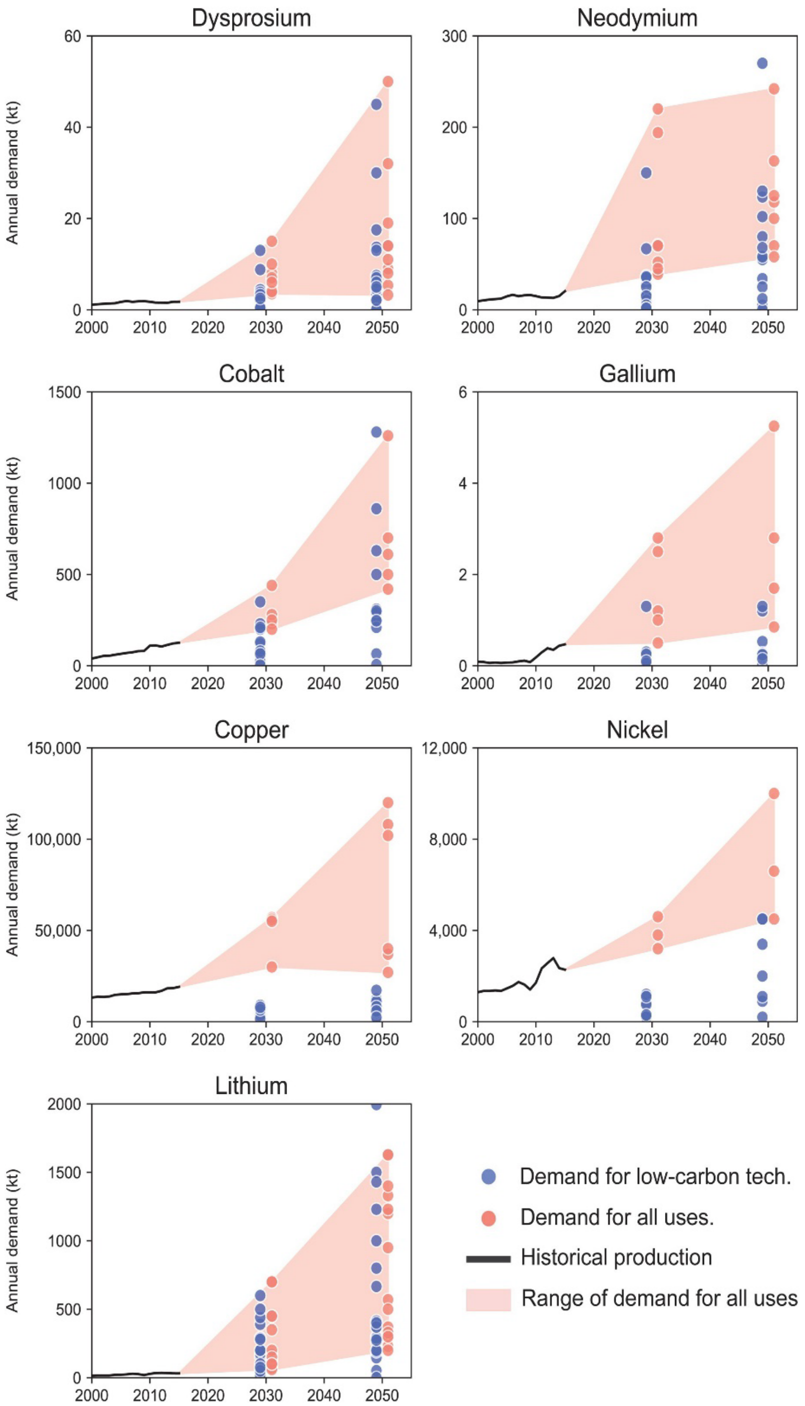
Long term projections of metal demand are based on growth of global population and wealth. Additionally, a number of metals used in key technologies – particularly those related to green power, green mobility and digitisation – are predicted to have exceptional growth,[22,23] although there is considerable variation between studies.[23] A compilation of predictions (Figure 2) shows that lithium demand in 2050 could be between 6 and 50 times greater than 2015 levels; cobalt 3 to 10 times greater, and the rare earth elements 2 to 28 times greater. The growth of renewable power – particularly when considering 'net zero carbon' ambitions [2,24] – will move the world's economies from a fossil fuel basis to one of metals.[25,26]

Figure 1: a) Global metal production and prices since 1920, showing metal production. Note variable units on vertical axis: million metric tonnes for aluminium and copper, 100 million metric tonnes for iron, and world population in billions. Metal prices corrected for inflation by indexing to 1998 US Producer Price Index. Metal production has steadily climbed over the last century, with a boom in consumption in the early 2000s, reflecting the growth of China in particular. This drove price rises in the early 2000s after decades of falling prices, but ended with the global 'Credit Crunch' in 2007 which led to metal price volatility.



Source: Metal data from United States Geological Survey,[27] population data from United Nations.[28]

Figure 2: Compilation of projected demand to 2050 for selected metals used in clean energy technologies, in units of thousands of metric tonnes. Each spot represents a different scenario or projection of demand, with pink spots showing studies that consider all metal uses, and blue spots showing demand from low carbon technologies only. Example technology uses include wind turbines (dysprosium, neodymium), batteries (lithium, cobalt, nickel), solar panel (gallium). Modified from Watari et al. 2020.[23]



1.2 Resource depletion

Data from operating mines from around the world indicate that the industry is exploiting ever-poorer ore bodies, and that this is contributing to greater environmental, social and cost footprints

Several studies argue that the Earth has limited amounts of minerals and metals that can be extracted, and that we are close to exhausting them.[29] However, this assumes that ore *reserves* and *resources* are physical entities, when in fact they are defined by economic and technical factors which often vary as a function of demand. In many mine sites, ore reserves increase with continued extraction, as companies continue to explore and increase their knowledge and economic forecasting of an ore body.[30] More details on the definition of reserves and resources are included in the Annex.

The alternative view of resource depletion is that the availability of metals is not set by a strict physical inventory of the Earth's crust, but defined by how much society is willing to pay in terms of economic cost, and social and environmental impacts.[29] In this view, the quality of an ore deposit is an important measure, as lower quality (smaller, lower concentration of metal, deeper) deposits have greater costs and impacts associated with them. Data from operating mines from around the world indicate that the industry is exploiting ever-poorer ore bodies, and that this is contributing to greater environmental, social and cost footprints.[31–34] A number of experts in the field suggest that the future supply of metals will not be limited by how much metal is left in the ground, but by the environmental and community impacts that society is willing to accept.[35]

Mining deep seafloor resources (PN-508) is one proposed mechanism to expand the available inventory of metals. Mineral deposits have already been identified that could meet large parts of demand for cobalt and the rare earth elements. There are concerns regarding the environmental impacts of seabed mining, and uncertainty as to how other maritime industries including fisheries will be affected.[36] Governance structures are lacking, particularly for the parts of the seafloor beyond the territorial waters (22 km from a nation's coast) and exclusive economic zone (typically 370 km from the coast). The south Pacific nation of Nauru has recently triggered the 'two year rule',[37] meaning the International Seabed Authority (ISA) has until July 2023 to finalise regulations governing deep sea mining in international waters. However, environmental NGOs and scientists have called for the moratorium on this activity to continue given the likely environmental impacts,[38] and several large companies have said they will not use metals from this source.[39]

Criticality

Some metals are vital to modern technologies, yet their future supply is unreliable – due to geological rarity, technically challenging recovery and processing, or geopolitical threats to supply chains. Some materials are defined as *critical* because of their importance to the economy, national security, and if they are at high risk of supply disruption (PN-609). A number of studies have attempted to quantify both importance and supply risk, and have compiled lists of critical metals.[23,40–43] Some of the critical metals (including rare earth elements, lithium, and cobalt) are needed for renewable

Renewable energy and low carbon technologies such as batteries, wind turbines and solar panels, may be dependent on one or more critical metals for their function.

power and low carbon technologies, and hence are projected to have big increases in demand.[23,44] The critical metals have seen increasing exploration activity, but for the most part, their total market share is small, and major mining companies have retained a focus on ferrous, precious and base metals.[45–47]

A number of critical metals are by-products of other metals, typically from processing of wastes and residues produced during smelting and refining of major metal ores (see Annex). Despite the projected and actual increases in demand for these by-products, their supply has not necessarily increased, and actual recovery remains much lower than the potential. While this means that there remains opportunities to increase by-product supply without opening new mines, it also indicates that by-product recovery has been unresponsive to market demands.[48] A significant proportion of the world's smelting and refining capacity is in China and SE Asia, so geopolitical factors are important even for metals that have broad geographical availability.

Renewable energy and low carbon technologies such as batteries, wind turbines and solar panels, may be dependent on one or more critical metals for their function. As part of the UK's Net Zero Strategy, HM Government has proposed an Expert Committee on Critical Minerals to advise on the publication of a UK Critical Minerals strategy in 2022, supported by a Critical Minerals Intelligence Centre to analyse stocks and flows of metals.[2]

Recycling

Recycling of metals is an important source of supply, as it reduces import dependence, and avoids some mining activity – and hence the environmental and social impacts of those mines. Recycling rates for some metals are high, based on them being high-cost commodities, used in specific forms in specific technologies (such as aluminium food and drink containers, lead-acid batteries). For many metals however, recycling rates are negligible at present (Figure 3), due to them being used in trivial amounts, in hard-to-disassemble devices that do not share common designs (such as mobile phones).[13,49] The inventory of 'used' metals embedded in end-of-life products is smaller than the projections of demand for many metals (Figure 2), and so recycling cannot be the sole supply of metal. The mining of geological sources will remain necessary without a significant reduction in demand.

Detailed statistics on recycling rates for specific metals are not available for the UK. Municipal waste in the UK contains approximately 1.5 million tonnes of metal per year, of which over 45% is captured for recycling.[50] In total (inclusive of municipal and commercial activities), the UK generates approximately 8 million tonnes of waste metal per year.[51] The UK exports over 15 million tonnes of scrap metal per year,[51] and most of the final recycling of metals is carried out overseas. The greater amount of metal exported as scrap than apparently generated as waste reflects differences between the reporting and classification of waste, versus export and shipping codes.

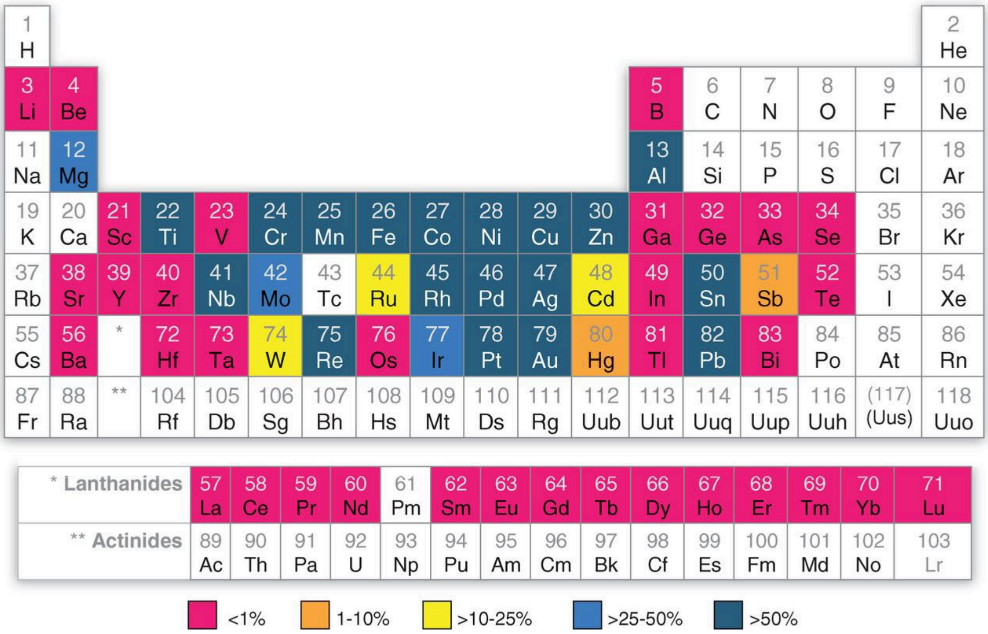
1.3 Metals in the UK

Mining, exploration and metal production

The UK's quarrying and non-metal mining sector produces construction materials (raw materials for cements and bulk aggregates) and a range of industrial minerals, including polyhalite deposits (a raw material for fertilisers) in North Yorkshire, and kaolin in Devon and Cornwall. The total value of UK production of construction and industrial minerals is close to £3 billion.[52] The value of current metal production is much smaller – approximately £30 million in 2018.[52] Much of this was driven by tungsten and tin mining operations at the Drakelands Mine at Hemerdon (near Plymouth, Devon), which ceased production in late 2018 after failing to meet production and financial targets.[53] The current owners intend to restart production in 2021.[54] The UK has industrial facilities involved in metal production, with smelting and refining capacity in aluminium, nickel, lead, iron and steel.

Several companies are actively exploring for and developing mines in ore deposits within the UK, including gold in Scotland and Northern Ireland, tungsten, tin and lithium in Devon and Cornwall, and lithium from geothermal brines in Cornwall. The Faraday Institute[55] supports commercial research into battery development, including domestic supply of raw materials.[55] Further support for the nascent UK lithium sector has come from Innovate UK.[56]

Figure 3. Global estimates of recycling rates for 60 metals and metalloids, circa 2008.[49]



UK agencies and regulators

Many mining companies, representing prospectors through to the largest multinationals, have UK headquarters.

In the UK, government oversight of mining falls across a number of public bodies and government departments. Strategic policies of metal supply, trade and use are within BEIS, DIT, and FCDO. The domestic environmental regulations that govern permits, such as monitoring and legal limits on water quality of discharges, are devolved:

- Defra and the Environment Agency are responsible in England;
- The Welsh Government and Natural Resources Wales in Wales;
- The Environment and Forestry Directorate and the non-departmental Scottish Environment Protection Agency (SEPA) in Scotland; and
- Department of Agriculture, Environment and Rural Affairs and its executive agency, the Northern Ireland Environment Agency (NIEA).

Legacy mines that need long term monitoring and maintenance may fall under the responsibility of the devolved environment agencies, but across the UK many are managed by the Coal Authority, an executive non-departmental public body sponsored by BEIS.

Planning decisions for mines in the UK are devolved to local authorities, known as Mineral Planning Authorities. These include unitary authorities, county councils and national park authorities.

All mineral rights in Great Britain are held privately, apart from precious metals (gold and silver) and fossil fuels, which, with a few exceptions, are held by The Crown Estate. There is no comprehensive and dependable registration of mineral rights. While the Land Registry does hold data on mineral rights ownership, the registration of rights is voluntary. Furthermore, mineral rights can be held and sold separately to land surface rights so do not always align. As a result, confidently identifying the owner of mineral rights is problematic. This system is an anomaly in comparison to other nations, including Northern Ireland where, with certain exceptions, mineral rights are held by the Department for the Economy.

UK role in the global mining industry

Many mining companies, representing prospectors through to the largest multinationals, have UK headquarters. As well as miners and explorers, the UK is home to globally significant and consultancies, service providers, industry associations and standards agencies for the mining industry.

Mining and metal production companies are well represented on FTSE and its sub-markets. UK-listed mining companies are responsible for over 50% of the world’s iron ore production, and a third of its copper. Over 5,000 further companies in the UK are associated with the mining supply chain. Whilst there are other mining hubs around the world, including Canada and Australia, the UK markets are home to the largest listings.[57]

UK institutions are major investors in the global mining industry, and as such can exert pressure on the sector, and influence decision-making. The recent

Investor Mining and Tailings Safety Initiative was spearheaded by the Church of England Pensions Board. With other major institutional shareholders, together holding $13 trillion in assets in the mining industry, they had sufficient combined influence to trigger a major review and new voluntary standards in tailings management.[58]

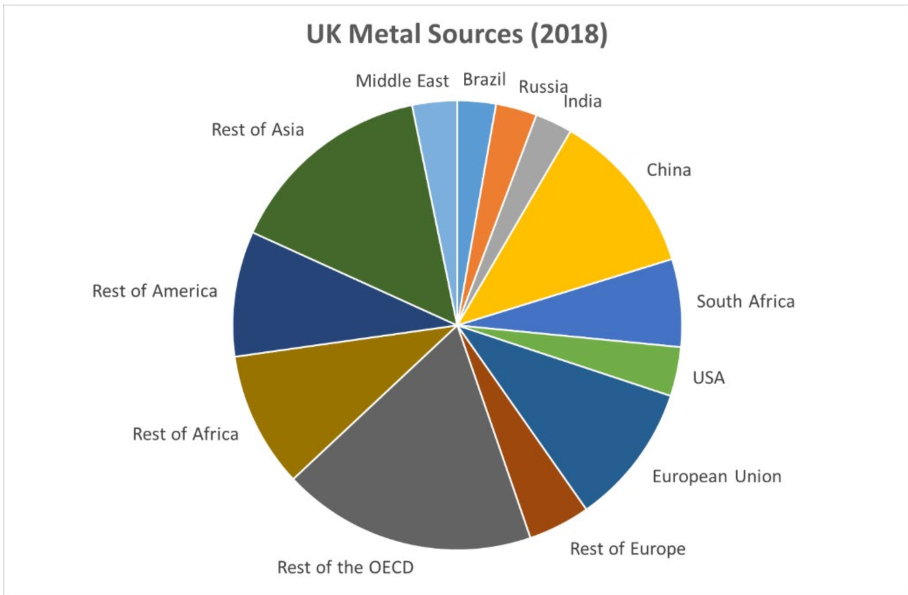
The UK is home to two of the world's most important markets for metals – the London Metal Exchange (LME), and the London Bullion Market Association (LBMA). The LME handled over $11 trillion of trades in 2020 in iron and steel, a range of base and precious metals, and some speciality metals. The LBMA cleared gold transactions worth $36.2 billion, and silver worth $7.48 billion, and had gold stocks in excess of $550 billion in September 2020.[59] As the largest global marketplaces, the LBMA and LME are influential stakeholders in the mining and metal processing industry. Certification schemes already in place include the LBMA's Responsible Sourcing scheme, covering 85–90% of annual world gold production from refineries, and the LME has ongoing consultation on how it can integrate metrics of sustainability performance with metal sales, including establishing a separate price for low carbon aluminium.[60]

As the host country for important companies, investors and markets relevant to metals, the UK can influence the global mining industry despite having little domestic metal production itself. The UK Government can enshrine regulations or reporting requirements into UK law, and compel UK-based or listed companies to comply, even if their mining operations are overseas. Examples of this include:

- Compulsory disclosure of climate-related financial information in line with recommendations from the Task Force on Climate-Related Financial Disclosures (TCFD) from 2022;[9]
- Greenhouse gas emission reporting, within the Streamlined Energy and Carbon Reporting (SECR) regulations;[61] and
- Legislation combating bribery and corruption.

The UK imports over 40 million tonnes of metal per year, from global sources (Figure 4). The international trade of metals is important to UK industry, but until the recent Net Zero Strategy,[2] the sourcing and supply of metals was not included in the UK's Industrial Strategy.[62] Some metals are available only from specific countries (see Section 0), and hence there is a growing geopolitical aspect to securing reliable supply of resources.

Figure 1: Source of UK metal imports (~40 million tonnes per year).[3]



2 The environmental and social impacts of mining

Mining may have both positive and negative impacts on the environment and people both near and far from sites, over timescales that may persist for decades or longer after extraction has ceased.

Mining may have both positive and negative impacts on the environment and people both near and far from sites, over timescales that may persist for decades or longer after extraction has ceased. This section outlines the nature of impacts in key thematic areas:

- land and biodiversity;
- water;
- energy and greenhouse gases;
- air quality;
- waste; and,
- social impacts.

Within each thematic area, there is a brief introduction as to how mining and mineral processing cause those impacts. The Annex provides some additional technical detail on methods and techniques used in industry to provide some further context. The outcome of those impacts on the natural environment, human health, and community outcomes is briefly summarised, and finally, some of the steps taken to mitigate and manage the impacts are described.

2.1 Land use & biodiversity

Mining and mineral processing uses less than 0.02% of the Earth's surface,[4] but land use changes within that footprint are often drastic and irrevocable, and mines may have indirect impacts over a much greater area than the mine site itself. The land surface uses of a mine may include a pit, industrial facilities including mineral processing equipment, roads, waste dumps and worker housing. The world's largest mines may have significant construction of facilities further away from the mine itself, including ports, freight railways, and power stations. Mining activities lead to the development of infrastructure, urban and industrial areas, and other commercial activities including agriculture in locations that would have been otherwise inaccessible without the mine and its transport links.[63,64] Through this associated development, mining contributes to much larger areas of deforestation, ecosystem degradation and landscape change than the footprint of the mine would imply – mines may have a zone of influence that extends over 50 km from the mine itself, with regards to direct and indirect deforestation.[5]

Mining is a driver of deforestation and forest degradation. Most present day mining in forests is in northern hemisphere evergreen forests, with just 7% of operating mines in tropical and subtropical forests, but this figure is growing.

Mining operations can permanently modify the land within their footprint – removing hills, digging pits, and constructing new raised areas of waste. When mining has ceased, mines may be backfilled by waste. However, for most mines, backfilling is not done due to cost.[65] Open pits may be left to fill with water. In some cases, pit lakes are used as water sources for other mining, industrial or domestic water supply; as a community amenity; and as aquatic nature preserves.[66,67] However, the legacy may not be positive, and the lake may need costly and long term interventions to reduce environmental impacts on water quality in particular (see Section 2.2).

Impacts of land use

Mining leads to changes to the land itself, often with little chance of restoration to a natural state.[68] As the location of a mine is primarily dictated by the geology, mines and exploration sites may be located in undeveloped areas, including intact forests and key biodiversity areas.[69] Mining may be the first human activity in such ‘frontier’ areas, and brings greater chance of disruption to indigenous communities, high biodiversity wilderness areas and fragile ecosystems that are otherwise barely disturbed by human activity.[69]

Mining is a driver of deforestation and forest degradation. Most present day mining in forests is in northern hemisphere evergreen forests, with just 7% of operating mines in tropical and subtropical forests, but this figure is growing.[70] Mining contributes to around 7% of annual global forest loss [5,6] and so in turn, to greenhouse gas emissions (13% of global GHG emissions are from deforestation).[71]

Within the zone of influence of a mine, biodiversity may be impacted through habitat loss, degradation and fragmentation; water contamination and consumption; disruption to animal migration pathways; and other threats associated with human activity (hunting, use of agricultural chemical, introduction of non-native species, exposure to novel zoonotic pathogens).[72] Biodiversity loss and habitat degradation have consequences for other economic and social interests[73] in mining districts, as the loss of ecosystems services can impact on agriculture, fisheries, forestry, rural settlements, and tourism.

The modification of the landscape can introduce hazards. Deterioration in vegetation cover and soil quality can lead to increased sediment run-off, increased flood risk, and other consequences downstream of mine sites.[74] Slopes (including those of waste piles) may be subject to slips and failures (examples include the Bingham Canyon mine landslide, Utah, USA, in 2013 with no loss of life; Brumadinho tailings dam failure, Brazil 2019, with 270 lives lost). Underground workings may cause sinkholes and subsidence at the surface. Subsidence at the Kiirunavaara mine, Sweden,[75] has led to the relocation of the overlying town of Kiruna.[76]

Mining’s impacts upon the land can be a source of conflict with communities and regulatory bodies. Issues range from loss of access, loss of livelihoods, and increased risk (or fear) of hazards. Land use conflicts are particularly marked in cultures that consider land ownership ancestral, or attach spiritual or religious value to the land and features within it. Mine sites have displaced or destroyed settlements and sites of cultural significance, including places of worship and sites of archaeological relevance, with a notable example of Rio Tinto's destruction of the Juukan Gorge site in Australia (see Section 2.6).

Management and mitigation of land use and biodiversity

Land use and biodiversity impacts and mitigation are covered by a number of regulations across the mining industry – including local environmental laws, conditions from investors and lenders (such as the Equator Principles),[77] and voluntary disclosure schemes (such as GRI reporting, and IFC Performance Standards)[78] including mining and metal specific schemes (such as the Aluminium Stewardship Initiative)[79] that report performance to markets.

Best practice in the mitigation of land use and biodiversity impacts is to follow a hierarchy of avoid, minimise, rectify/ restore and offset[80] (PB-34). Many of the schemes listed above use this hierarchy.

Avoid

Existing land use classifications (such as national park, Natura 2000, or UNESCO World Heritage status) may limit or prohibit mining activities to protect areas of environmental or cultural significance. However, over 6% of protected areas (PA) worldwide have mining operations within their boundaries,[81] and other protected areas may be subject to downgrading, downsizing, and degazettement (PADDD; see Figure 5).[82] PADDD events driven by mining and mineral exploration have been identified across Africa,[83,84] the Americas,[82,85] Asia,[86] and Oceania.[87]

The International Council on Metals and Mining (ICMM; an international membership organisation founded in 2001 to improve sustainable development in the commercial mining industry) has a position statement on Mining and Protected Areas[88] that outlines commitments to respect legally designated protected areas— and not to mine if it would be incompatible with the biodiversity value for which a PA was designated. The ICMM recognises that classification of a PA under national or international law "should be transparent, rigorous, based on scientific and cultural understanding, backed by legal controls, and should contribute to the equitable resolution of different land-use, conservation and development objectives".[88] The ICMM recognises that decision making regarding mining projects in PAs should take into account community opinion and impact; whether there are other development opportunities if mining projects are foregone; whether there is a history of mining in the PA; and if there are 'clean' mining and processing technologies available. Against these criteria, the ICMM agreed in 2003 that UNESCO World Heritage properties would be 'No-go areas' for exploration and mining by its member companies.

Figure 5: Protected area downgrading, downsizing and degazettement (PADDD) allows for mining operations on lands that would previously have forbidden it. The zone of influence of mines mean that sites outside the boundaries can negatively impact the PA.

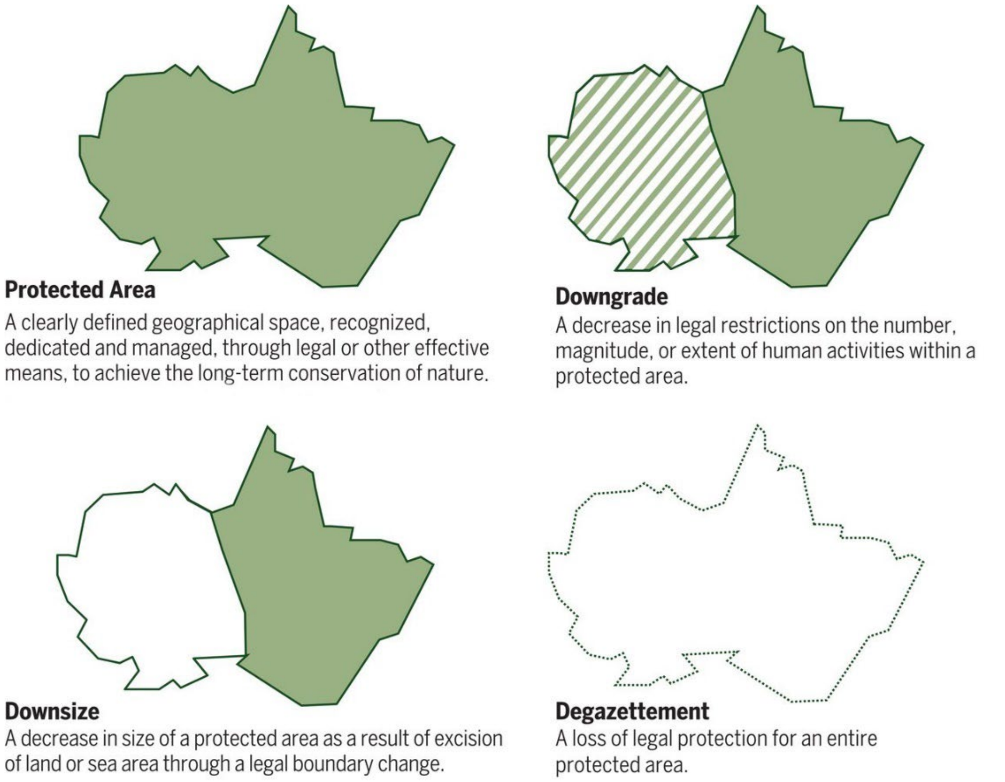


Figure modified from[85]

No other national or international designation of a PA is considered a No-go. Mining and exploration continues by a number of non-ICMM members in World Heritage properties, such as the UNESCO-recognised Cornwall and West Devon Mining Landscape World Heritage Site, which has a management plan that permits proposals for mining "where they do not adversely affect the outstanding universal values of the site".[89]

Avoidance is the most effective means of minimising environmental harm.[80] Avoidance may not necessarily mean halting a mining project in planning or even in operation — the impacts may be restricted in space and time (such as the seasonal migration routes of key animals), and there are planning decisions in mining that mean specific actions may be avoided (such as road construction). The Cross Sector Biodiversity Initiative[80] (CSBI, a partnership between extractive industry bodies including the ICMM, IPIECA and investment and development banks including the International Finance Corporation that are part of the Equator Principles) regards avoidance as the most cost effective approach to mitigating biodiversity impacts, but recognises that there may be cost disincentives. Mining can be an important source of employment and government revenue (see Annex), and so forgoing a mine project might hamper sustainable development opportunities elsewhere in the country. CSBI recommend cost benefit analysis to determine the best options; however, calculating the value or worth of nature and biodiversity, and the benefits and services it provides is a challenging and evolving field. The Treasury recently issued the 'Dasgupta Review' on the Economics of Biodiversity that detailed both the need and the obstacles to valuing nature.[73]

Around 13% of global GHG emissions are from deforestation and forest degradation. Due to the ability of forests to passively remove CO_2 from the atmosphere, avoiding deforestation could mitigate and offset as much as a third of global GHG output.[71] One mechanism to reduce deforestation was introduced within the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement 2015. "Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries" (REDD+; see PN-466) compensates countries for reducing emissions by avoiding deforestation. The World Bank's Forest-Smart Mining initiative[70] considers REDD+ (as well as voluntary carbon schemes) an important – yet underused — tool in policy and decision making for mining, and incentivising 'forest-smart approaches', filling a "governance void" for mining.[90]

Minimise

Minimisation methods include adoption of best practice and best available technologies during operation. Specific to land use and biodiversity impacts, these might include damping noise, planning of roads to minimise habitat fragmentation, use of low intensity lighting, and stabilisation of slopes with native vegetation.

A mine site's footprint may be minimised by exporting materials out at an earlier stage of processing, by shipping / selling concentrates or even mined ore without further processing, smelting and refining. Those processes and their impacts will still occur elsewhere however, and companies that operate with less integration on a site will lose value from the product, and contribute to greater energy consumption and emissions through freight.

Underground mining typically has a lower impact on the land surface than open pit methods. Underground methods such as block caving mean that lower value, bulk tonnage ores can be extracted economically from underground operations, and increasing use of automation and remotely operated equipment are improving the safety, and increasing the reach of underground mining operations.[91] The void spaces created by underground mining can also be used for waste disposal, with tailings dewatered and backfilled.[92]

Restore

Restoration occurs after impacts have been realised, and as such tends to focus on post-closure rehabilitation of mine sites. Best practice is for restoration to occur throughout a mine's life where possible, rather than just post-closure. Ongoing restoration efforts include management for soils removed during mining, so that they can be used to rehabilitate parcels of land. Similarly, plants, seedbanks and nurseries may be used to preserve vegetation and allow for the recovery of a site to the original flora.[93,94] Some plants can help to immobilise toxic metals in soils and prevent further contamination. These plants may be deliberately used to extract metals from soils to reduce contamination (known as 'phytoremediation') or as a potentially economic means of production ('phytomining').[95]

Rehabilitation to original or novel ecosystems, or reclamation of the land to useful alternative purposes, may be "challenging, slow and expensive".[80] In recent years, the mining industry has shifted away from a goal of rehabilitating land to an ambition of restoration,[96,97] demonstrating a 'beyond compliance' approach. However, this is not uniform across the sector, nor applied in all countries, with poorer restoration efforts in Africa for example.[98] The governance challenges in the artisanal mining sector mean that rehabilitation is rarely done in those settings.

Offset

Offsets are defined as "Measurable conservation outcomes, resulting from actions applied to areas not impacted by the project, that compensate for significant, adverse impacts of a project that cannot be avoided, minimized and/or restored".[80] Offsets may be incorporated into a 'No Net Loss' or 'Net Gain' scheme (PB-34), as required by the host country, or voluntarily. Offsets and NNL have become a popular tool for mine developers and regulators, but have been subject to criticism:

- Overall they facilitate development rather than conservation,[99] including in protected areas. Offset areas may be later developed. Without conservation in perpetuity, offsets result in net development rather than conservation;
- Purchased offsets generate income for conservation goals already met, at the expense of further losses elsewhere;[100]
- The measurement of biodiversity — and hence the metrics of success for an offset — is difficult [80,101,102]
- Offset areas may not be ecologically equivalent to the project areas;[103]
- Offsets may undermine the higher tier mitigation options. [104]
- NNL schemes struggle to demonstrate true success, and there are issues with how performance is measured and shown in reliable metrics.[103]

Artisanal and small-scale mining

Most artisanal mines are informal and many operate without full permissions, including in protected areas.[105] Consequently there may be limited environmental management, and post-mine remediation is rare. The role of artisanal mining in direct deforestation is minor, and on the whole it is less likely to facilitate further formal industrialisation than commercial or large-scale mining, but artisanal and small-scale mining may lead to the proliferation of other informal livelihoods that exploit natural resources, such as logging.[106] However, 'rushes' of many miners into an area, and

Box 1 Alcoa's jarrah forest rehabilitation

Alcoa's bauxite mining operations in Western Australia have long been under scrutiny for their environmental footprint, given their proximity to the population centre of Perth, and its drinking water supplies.[107] Alcoa's attempts to restore ecosystems, and to go beyond reclamation or revegetation, are a response to that scrutiny, and an ambition to stay ahead of minimum legal requirements.[107]

Bauxite mining began in 1963, and early remediation (1966) consisted of planting mined areas with exotic pines, but by the mid 1970s, rehabilitation was using native plants including jarrah, an endemic eucalyptus tree.[108] Rehabilitation steps include:

- Baseline flora and fauna surveys;
- Seed and plant collection;
- soil removal, preservation and reuse;
- Re-landscaping after mining;
- Replanting from seeds and nurseries and construction of natural habitats. [93,108]

There are no simple measures of whether a piece of land has been fully restored, but Alcoa's rehabilitation of the jarrah forests suggest that mined areas can show recovery of vital ecosystem functions (such as nutrient cycling) and services (including lumber, recreation, water catchment and storage).[107] Some key measures such as biodiversity fail to recover though, as the rehabilitated landscape lacks some of the ecological niches that are associated with old growth and mature ecosystems.[107]

intensification of artisanal and small-scale mining activity may (rarely) result in the development of mine sites that rival large-scale commercial operations in size and impact.[106,109]

Poor practice during operation, and lack of remediation post-mining, mean that contaminated land is a potential consequence of artisanal mining. This can lead to contamination of drinking water, soil, agricultural land and foodchains, and associated impacts on human health [110,111] (see also section 2.2).

ASM-specific certification schemes such as Fairtrade and Fairmined [112,113] include standards on environmental footprint that demand compliance with local laws and protected area restrictions, require backfilling of voids and revegetation post-mining, and restrict the use of reagents known to have environmental legacies (such as mercury). However, there is scope for better alignment with other land-use governance schemes or specific provisions for biodiversity, forestry and competing land uses.[113]

2.2 Water

All stages of mining activity, from exploration to closure, use water. This water can become contaminated with the chemicals used in mineral processing, or by the metals dissolved out of ores. The contamination of water can continue long after mining has ended by reactions between water and mine waste. There are two main impacts on water from mining:

- the use of water, particularly in areas where fresh water is scarce;
- effects on water quality contamination of ground and surface water.

Water use and management

The overall consumption of water in mining and mineral processing is modest compared to other industries. The production of aluminium, iron, copper and gold together use approximately 0.09–0.15% of total water withdrawn and 0.46–0.78% of industrial withdrawals.[114] However, the mining industry produces small volumes of high value products. When water consumption is viewed in terms of how much water was needed to produce the final metal (a metric known as 'intensity'), then mining is revealed to be a water-intensive process. By example, the production of a tonne of copper requires over 170 tonnes of water on average.[115] The water intensity varies between metals, ore types, and in particular, ore grade (the concentration of metal in the ore) with little evidence of economies of scale and greater water efficiency of larger mines.[115] This intensity of water use becomes particularly significant when mines are located in arid climates.

Water is used throughout the mining life cycle, but the greatest use is during mineral processing, in which water is used for dust control, as a coolant, in solvents, and to transport material around facilities.[116] Further details on processing techniques are provided in the Annex. Water-dependent processing methods are commonplace even in semi-arid and arid climates.

One form of lithium mining is dependent on the extraction and processing of saline brines. In the 'Lithium Triangle' of South America (spanning a border region of Argentina, Bolivia and Chile), lithium-bearing brine is extracted from high altitude salt lakes known as *salars*. While there is debate other whether the lithium brine should be classified as water,[117] its extraction can impact the hydrogeological regime (the distribution and movement of groundwater in rocks and soils, PB 40) of the surrounding areas and is a source of conflict with local communities.[118]

Mining operations obtain water from surface water, groundwater (including water pumped out of mines), intercepting rainfall, and from commercial supplies.[119] To limit the accumulation of unwanted water in mine workings, operators intercept springs and streams, and pump to dewater the mine. This water may be used on site, or discharged as unwanted excess. Some of the largest mining operations own or will construct desalination facilities to make use of seawater or saline lakes.[120,121] Where desalination plants draw on

The competition for water resources is a source of tension and conflict between mine sites, and nearby communities and industries

seawater, there are impacts in terms of the greatly increased energy inputs needed,[115] and increased costs for the mining companies — water-related infrastructure accounts for ~10% of the mining industry's capital expenditure.[122]

Water will be lost from a mine site by evaporation, percolation into groundwater, and by deliberate or accidental discharge to surface water courses. Mining and mineral processing operations will attempt to reduce or offset their net water demands by recycling and reusing water. Operations in more arid climates lose more water through evaporation, and thus have a greater demand on water supplies, rather than their own recycling.[31]

Impacts of water use

The competition for water resources is a source of tension and conflict between mine sites, and nearby communities and industries.[123–127] The withdrawal of water for and on mining sites, and their storage and recycling of water on site, reduces the available water in natural systems and for other industrial and social uses (including fisheries and agriculture). Between 2000 and 2017, 58% of mining cases lodged with the International Finance Corporation's Compliance Officer Ombudsman were related to water.[122]

The mining industry's management of water may modify water supplies off site, by lowering groundwater water levels, reducing river and stream flows, and placing barriers between headwaters and downstream waters.[128] A river must maintain a minimum 'environmental flow' to preserve its ecological function.[129] In some jurisdictions (such as Chile and Australia) the environmental flow is an allocated (i.e. legally protected) use of water from a river.[130,131] The modifications to river flow have consequences on ecosystems, and result in impacts such as loss of biodiversity, changing plant cover, and flooding.[129]

Management and mitigation of water use

The management of water on a mine site is necessary in both water-rich and water-scarce environments, as operators need to limit freshwater contamination and flooding in the former, and excessive losses / consumption of freshwater in the latter. Water management both on mine sites and in competing industries within the same catchment as the mine are seen as the key methods for reducing pressure on water resources.[122]

The reporting of water consumption by mining operations is complicated by how they classify recycled water. Whilst some use the term only to describe water recovered from the processing and decontamination of effluents, other operators describe water pumped from mine workings or intercepted from surface runoff and rainfall as recycled.[132] Water reporting by mining companies, including less-technical disclosures to near-mine communities, and joint data collection initiatives with local communities, are seen as best practice in reducing tensions and aiding appropriate allocation of resources.[122]

Water quality

Water used on a mining site can become contaminated with metals, solvents and other chemicals used in mineral processing.

Water used on a mining site can become contaminated with metals, solvents and other chemicals used in mineral processing; and solids, such as particles of mine waste. In many cases, mine operators capture contaminated water on site and treat before discharge or reuse. However, mismanagement of water and effluents can release metals and reagents used in mineral processing, such as cyanide, into rivers and groundwater.[133–135]

The mismanagement of waste, either by accidental failure of waste dumps or by deliberate disposal into rivers, can contaminate water.[136–138] Some mines deliberately release waste into rivers – although 'riverine tailings disposal' is now rarely practiced by major commercial mines, a small number still use it (three in Papua New Guinea, one in Indonesia)[139] due to poor ground conditions for conventional tailings storage facilities.[140] Artisanal and small-scale mining operations around the world may deposit waste in rivers.

Contamination can also occur as minerals in ores and waste dissolve into water. While this can occur naturally, mining exposes greater volumes of material to water and air, accelerating the breakdown of minerals.[141,142] This causes 'acid mine drainage' (or acid rock drainage),[141] and releases both acids and dissolved metals such as copper and arsenic to rivers.[143] Acid mine drainage (AMD) can continue long after mining activities have ceased, and indeed can worsen after mining has ceased as water management and treatment on the site ends. Approximately 3% of the UK's rivers (1,500 km) are affected by AMD from thousands of legacy mine sites, including coal. Impacts can be severe, with reduced aquatic wildlife, biodiversity and impaired ecosystems (see Box 2).[142]

Impacts on Water Quality

Commercial mining operations manage water to avoid the release of contaminated waters, but accidental spillages, leakages and failures have occurred, with release of significant volumes of contaminated water or concentrated reagents (such as the tailings dam failures at Mount Polley mine, Canada in 2014; Brazil's 2015 Mariana tailings dam disaster; the 2000 Baia Mare, Romania, cyanide spill into the Danube; and Hungary's 2010 Ajka alumina plant 'red mud' spill disaster). The contaminants released in major accidents and small, uncontrolled discharges can have toxic effects on plants, animals or micro-organisms in freshwater systems, and on human health through consumption in drinking water or food.[144,145]

The impact of major accidents on the natural environment and communities both near and far to mine sites have led to negative opinions on mining and mineral processing; the use of cyanide in gold processing has poor public acceptability, and a number of mining jurisdictions will not approve its use[146] (leading to export of gold-bearing concentrates for processing and refining elsewhere).

Box 2 Wheal Jane, Cornwall

The Wheal Jane tin mine in Cornwall had an extensive underground network of shafts and tunnels that needed constant pumping to prevent flooding.[147] After a drop in the tin price in 1991, the mine closed, and the pumps were turned off. Water levels rose, flooding the underground tunnels and eventually reaching the surface. Some pumping resumed, and surface openings that had begun discharging minewater were plugged and sealed.

On January 13th 1992, a large volume of contaminated water was released from underground into the Carnon River and Fal Estuary. The outburst of water was possibly the result of an underground collapse, or the failure of a plug in a surface opening to the mine. The discharged water was acidic and metal-rich, and zinc and cadmium levels in the Carnon river exceeded Environmental Quality Standards by 900 and 600 times respectively.[147] The discharge formed a conspicuous orange plume that attracted considerable media attention. After the initial outburst, a consistent flow of contaminated water continued into the Carnon River.

Short term mitigation was put into action, with pumping capacity at Wheal Jane increased, and water treated to neutralise acidity and remove metals.[147] By 2000, a long term active treatment facility was operational. Water was pumped and treated on the Wheal Jane mine site, with solid metal-rich waste disposed of in the Wheal Jane tailings storage facility.[148]

Pumping and treatment continues today, and for the foreseeable future. The Coal Authority, acting on behalf of the Environment Agency, has responsibility for the Wheal Jane water management. The Wheal Jane site has otherwise been repurposed into a Science Park, incorporating business units, restored wildlife habitats and a ~1.5 MW solar farm — but water treatment and associated waste disposal into the tailings facility will continue for at least the next few decades.

Rivers and lakes systems can be contaminated with excess solids, either through riverine tailings disposal, tailings dam failures, or unmanaged surface run-off over unconsolidated mine waste. Increased sediment in rivers change the water quality, blanketing vegetation as it settles, and smothering banks and floodplains during flooding.[149–151] As sediment deposits, it can modify the morphology of channels, and hence the flows, flooding regime and course of rivers.[152] These hydrological changes in turn impact on the aquatic and near-river ecosystems, and the services they provide (including fisheries, irrigation, potable water supply, and amenity use).

Management and mitigation of water quality

As most mineral processing techniques use water, some contamination of water used on site is almost inevitable – water quality impacts are best avoided by isolating water on the mine site from the wider environment, and treating or reusing before any discharge can occur. Long term acid mine drainage, can be avoided by adding neutralising agents to acid-producing waste piles.[153]

The recycling of water and effluents on site may not require significant treatment of water to remove dissolved chemical or suspended solids, so the reuse of water retained on site is a cost-effective means of handling both discharge and supply. Some contamination, including solid particles, can be easily removed by just collecting water in settling ponds. Other contaminants in the water will persist for long periods,[144] and require more treatment, such as pumping contaminated water through filter and reaction vessels, or gravel beds with limestone or chalk to neutralise acids.[154] Plants and algae may also be used to remove chemicals from the water, including heavy metals.[95,155]

Some forms of mineral processing use solvents to break down minerals and to extract metals. Powerful acids are often used, requiring careful handling and neutralisation of spent solvents and waste. Alternatives to the use of acids and cyanide include the use of microbes to release metals from minerals, organic acids, ionic liquids, and deep eutectic solvents.[156–159] Although these novel solvents may allow for safer handling and disposal, and may improve the recovery of metals, it should be recognised that that these alternatives may not be equally efficient, or ready for industrial application. Some of these are water-free, and so can reduce water consumption.

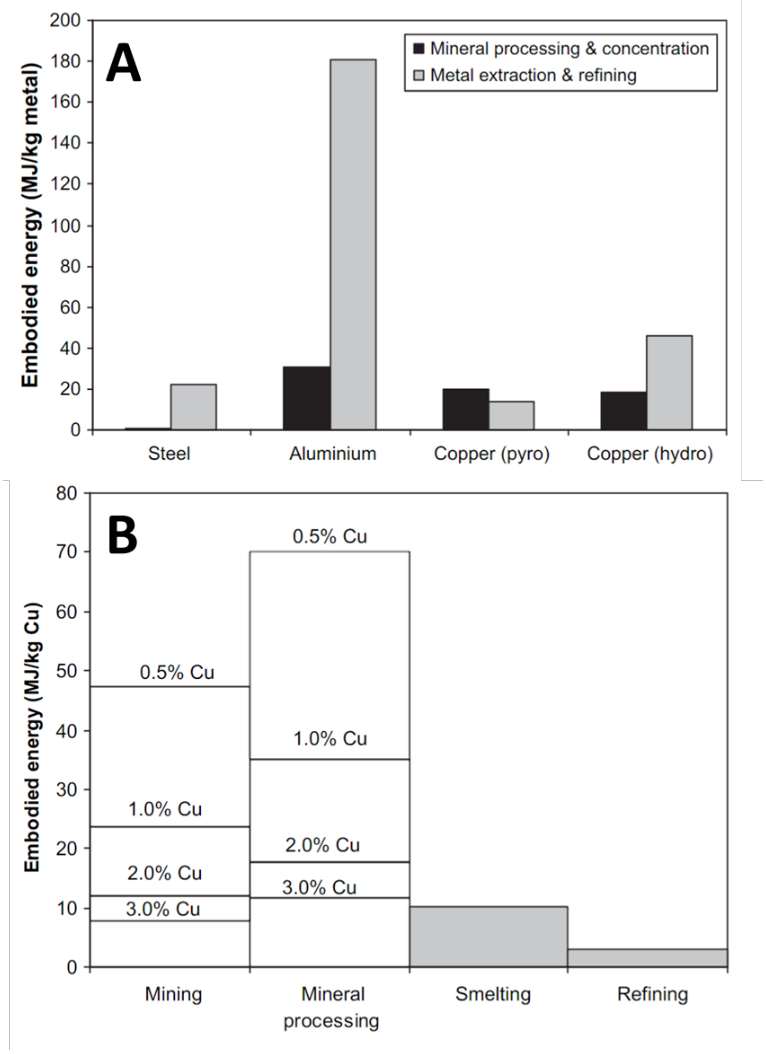
Good practice in water management is typically followed by artisanal and small-scale miners certified by ASM certification schemes such as Fairmined or Fairtrade, which have restrictions on the discharge of waste in to waterways, and the use of reagents known to pose a threat to freshwater (mercury and cyanide). However, where ASM is unregulated or informal, good practice in water management is often ignored, and there is uncontrolled release of waste and reagents, with resulting environmental and human health impacts.[109,160,161] As many ASM activities lack access to initiatives that would support their professionalization and formalisation, they cannot participate in Fairmined and equivalent certification schemes [162,163] and so ASM-derived water contamination remains an ongoing problem.

2.3 Energy and greenhouse gas emissions

Mining and mineral processing are energy intensive operations, representing more than 8% of the world's annual energy usage.[164,165] Some metals and types of mining are more energy intensive than others, with the production of aluminium being a notable consumer of electricity (Figure 6). Lower grades of ore lead to more energy during mining and mineral processing; smelting and refining are less impacted.[166]

A range of energy and fuel types are used within the mining industry. Fossils fuels including diesel and fuel oil are vital for exploration and early mine site activities in remote locations. Most mine vehicles are fossil-fuel based.

Figure 6: A) Embodied energy (per unit metal) for major industrial metals and production ore types of copper. Aluminium in particular requires significant energy inputs during the refining of ores. B) Impact of declining grade on embodied energy requirements of copper production. As the concentration of copper in the ore decreases from 3% to 0.5%, the energy demands of mining and mineral processing rise. 'Pyro' refers to pyrometallurgy (using heat to recover metals from minerals, typically in a smelter) and 'hydro' is hydrometallurgy, in which solvents are used to extract the metal.



Source: Figure modified from [166]

The true 'intensity' of CO_2 emissions per unit metal is difficult to estimate, as different producers release data using different methodologies

Smelting and roasting of ores often use fossil fuels to achieve the high temperatures needed. Steelmaking in particular relies on coal not just for heat, but for the metallurgical process too — the coal-dependent blast furnace method accounts for 90% of steel production from iron ore[165] and 71% of all steel including recycling,[167] representing approximately 12% of global coal consumption per year. The steel industry's use of coal means that it contributes to around 8% of the world's annual CO_2 output [168,169] (with the whole mining and mineral processing industry contributing approximately 10% of annual CO_2).[7]

Mining and mineral processing may draw electricity from a commercial grid supply, but the largest operations may establish their own means of generating electricity — typically fuel oil or coal-fired power generation, but with more recent plans including solar power.[170–173] Some mineral processing operations have large electricity demands — the electrolysis by the Hall–Héroult process represents 95% of the electricity consumption of aluminium production.[174] As a result, aluminium smelters/ refineries often locate in areas with cheap electricity, such as near sources of hydroelectric and geothermal power.[173] Over 25% of the electricity used for aluminium smelting comes from renewable sources.[175]

The power consumption of mining and mineral processing has associated CO_2 emissions. Reporting of CO_2 emissions to investors typically use the terminology of the Greenhouse Gas Protocol Corporate Accounting and Reporting Standard[176] to distinguish:

- Scope 1 emissions generated on-site by fossil fuel use and electricity generation;
- Scope 2 emissions generated off-site by third parties in the supply of electricity ;
- Scope 3 or 'value chain' emissions generated by third parties and represent CO_2 associated with the production of goods and services used by mining companies, and the emissions associated with the use of the companies' products.

The true 'intensity' of CO_2 emissions per unit metal is difficult to estimate, as different producers release data using different methodologies, with significant variation over the reporting of Scope 3 emissions in particular.[12,31] Further variation comes about through the geological differences between orebodies; the energy blend in electricity supply (i.e. Scope 2 CO_2); mining and processing methods; CO_2 associated with reagents, shipping, offsite processing, smelting and refining (Scope 3); and variability of emissions as a consequence of ore quality including grade.[31]

Impacts of energy use and GHG emissions

The mining industry contributes approximately 10% of the world's annual CO_2 emissions.[7] Emissions increase with increasing metal demand, and decreasing ore quality (Figure 6). Both of these issues are predicted to continue and intensify in the coming decades, and particularly so if policies

The production of steel generates 8% of the global annual anthropogenic output of CO2, and so decarbonisation of steel is an important pillar of net zero ambitions

drive growth in more metal-intensive low-carbon technology. It should be noted that whilst mining and mineral processing are a source of CO_2 emissions, the metals produced are necessary for achieving net zero carbon emissions.

Anthropogenic climate change poses a material risk to mining and mineral processing operations.[177–179] Extreme weather events can interfere with operations, and higher rainfall and seasonal storm activity can reduce the stability of waste piles and tailings storage facilities (see Section 2.5). Drought conditions are a challenge to water supply for mining. Coastal mine sites and infrastructure including desalinisation plants and ports are at risk from inundation due to sea level rise.

Reducing energy use and GHG emissions

Operational efficiency in mining and mineral processing operations can lead to small but cost-effective reductions in energy consumption; a 2013 report on Australian mines indicated that they could reduce energy costs by 10–20%,[180] by the accumulation of small measures such as optimising the operation of extractor vehicles, and reducing the gradient of mine-site haulage slopes.[181,182] Crushing and milling of rocks consumes about 1.8% of the world's annual energy production,[183] and is widely considered to be energy-inefficient.[184] Various studies suggest energy savings of 5–30% could be achieved across the mining sector by implementing already-available best practice, equipment and operating processes.[183,185] GHG emissions could be reduced by up to 10% and 20% in iron and gold mining with favourable costs.[186]

A review of energy reduction initiatives in the Canadian mining industry from the 1970s to present day found the "rate of uptake [of] suggestions seems to be low".[187] Energy-saving initiatives would be trialled and demonstrated, but not fully implemented. Other initiatives would be deployed, but only at one site or company, with no propagation of best practice or best available technology through the sector. This tallies with other studies that find a poor correlation between sustainability reporting and tangible improvements.[188]

The Internet of Things (IOT, PN-655) has the potential to make mining and mineral processing facilities data-rich and respond to the natural variability of ores in near-real time. Operators can analyse rocks during loading and hauling, to determine metal grades, mineralogy etc. and better decide how to process batches for enhanced efficiency. Better telemetry on vehicles and between facilities on mineral processing sites allows for better management, optimisation and enhanced efficiency, reducing energy and water consumption, minimising waste, and maximising metal recovery.[189]

The production of steel generates 8% of the global annual anthropogenic output of CO_2, and so decarbonisation of steel is an important pillar of net zero ambitions.[168,169] Alternatives to traditional coal-based blast furnace steel production include the use of biomass in lieu of coal, CO_2 capture and use or storage (CCUS; see PB-30), more recycling and reuse of scrap rather than virgin ore, and the deployment of hydrogen steel production. The last uses hydrogen to convert the iron ore to metal instead of carbon from coal, and so avoids CO_2 emissions. Hydrogen can be produced by electrolysis of water and is hence an electricity-intensive process. A conversion of the UK's blast furnace steel production to hydrogen would need more than 20 TWh of electricity – or 17% of all the renewable electricity the UK currently generates.[190] The IEA estimate that global electricity demand for steel production will increase by 60% by 2050 (relative to 2020 consumption), and will require the deployment of a 1 million tonne per annum CCUS installation every 2–3 weeks from 2030. [165]

2.4 Air quality & atmospheric emissions

Smelting and roasting of ore during mineral processing can release a range of gases with both industrial health & safety and environmental impacts.

Mining and mineral processing are responsible for a number of emissions in addition to those associated with energy. Smelting and roasting of ore during mineral processing can release a range of gases with both industrial health & safety and environmental impacts. The breakdown of sulphide minerals (found in ores of copper, nickel, lead and zinc, and as a minor component in coal) produces sulphur dioxide. The smelting of copper ore produces approximately 2 tonnes of sulphur dioxide per tonne of copper.[191] Sulphur dioxide emissions can spread over significant distances, generating impacts both near to the emissions source and at potentially transnational distances. Sulphur dioxide reacts with water in the atmosphere to produce sulphuric acid, which subsequently is deposited as acid rain.

Smelting is the main source of atmospheric emissions of As, Cu, Cd, Sb, and Zn, and a significant contributor to Cr, Pb, Se, and Ni.[192] Copper smelting alone generates 20–45% of the global atmospheric arsenic flux.[193] Emissions from mineral processing and metal extraction also include mercury.[17,194,195] Emissions relate to the quality of the ore deposit:

- Greater energy inputs, and hence fossil fuel burning and emissions, are needed for ores with lower grades / concentrations of target metals.
- Ores with a greater amount of unwanted metals (sometimes referred to as 'penalty' or 'deleterious' metals) that need to be removed during smelting result in more emissions or more toxic emissions.

Environmental and human health impacts from emissions

Sulphur dioxide released from the burning of coal or the roasting of sulphide ore reacts with water in the atmosphere to produce acid rain. This result in impacts on water courses and ecosystems, and was recognised in the 1970s as a regional and transboundary impact of industrial activity.[196,197] Acid deposition results in negative effects on plants, soils, freshwater and ecosystems.[198,199]

Mining and mineral processing, and particularly smelting, contribute to emissions of metals and metalloids to the atmosphere. This results in contamination of land, water and food, as well as direct human exposure to a range of toxic metals.[200] The human health impacts show a correlation with proximity to emissions sources.[201] Health burdens for various mining and mineral processing activities, expressed in disability adjusted life years, are summarised in Table 1.

Table 1 Global mining and mineral processing operations and their estimated health burden. Data from Pure Earth's "The world's worst pollution problems" 2016 report.[202]

Process	Estimate population exposed	Pollutants	DALYs †
Industrial mining and ore processing*	7 million	Cr, Pb, Cd, Hg, As	0.45 – 2.6 million ‡
Lead smelting	1.1 million	Pb, Hg, Cd	1 – 2.5 million
Artisanal-scale gold mining	4.2 million	Hg, Pb, Cr	0.6 – 1.6 million‡

* Includes tailings and wastewater exposure pathways.
† Disability adjusted life years. The sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability.
‡ Uncertainties in estimating health burden, calculating DALYs and lack of data regarding soil exposure pathways mean that the original report only reported data associated with Pb, Cr and in some cases Hg.

The processing of artisanal and small-scale-mined gold is often carried out with mercury amalgamation.[109] This method exposes the practitioners to mercury vapour inhalation, and as the process is often carried out over a stove, indoors, human exposure risks are high, and include other members of the household (including children). In informal mining communities, it is often women who carry out the mineral separation and amalgam processing.[203] Mercury exposure results in significant health impacts for adults, children, and foetuses, causing death, neurological damage, birth and growth defects, low IQ, autism and cerebral palsy and more (see Box 3).[204,205]

Management and mitigation of air quality and atmospheric emissions

Management of non-GHG emissions at smelters begins with avoidance; most smelters have specifications on what material they will accept from mines, with upper limits placed on so-called 'penalty' or 'deleterious' elements, which include those subject to stringent emissions regulations (such as As, Cd, and Hg). For example, only four smelters worldwide will accept copper concentrates with arsenic contents greater than 1%.[206]

Emissions at smelters should be scrubbed or filtered before discharge. Sulphur dioxide emissions can be reduced by techniques such as flue gas desulphurisation, where a slurry of calcium carbonate is sprayed into the exhaust gases, with chemical reactions removing the SO_2 into a liquid or solid phase. Other gases including vaporised metals can be removed by similar ‘scrubbing’ techniques, and dusts, aerosols and other particulates removed by filtration.[207]

Smelters release emissions through tall chimneys to facilitate dispersion and dilution; these have resulted in spatially extensive ‘haloes’ of contamination in surrounding areas, with greatest contamination closest to the emission source. Remediation options for contaminated land and water bodies include:

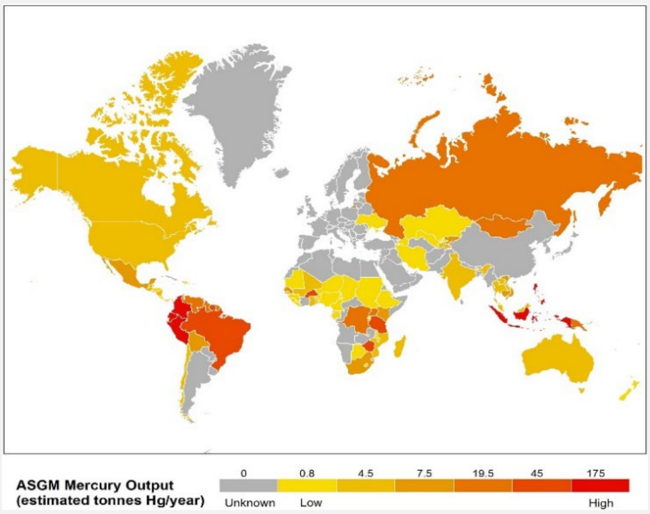
- Amendment, in which substances are added to the soil or water to neutralise, immobilise or stabilise contaminants
- Extraction, in which contaminants are removed from soil of water by washing, leaching, filtration, or ‘phytoextraction’ (growth, harvest and controlled disposal of plant species that accumulate the contaminants).[208]

3 Mercury

The United Nation's Minamata Convention on Mercury [209] was adopted in 2013, and signed by 128 countries. The Minamata Convention aims to control, reduce, or eliminate sources and use of mercury.[210] Artisanal small-scale mining (ASM) and processing of gold is the greatest source of mercury contamination and human exposure,[205] with around 2000 tonnes of Hg released per year, with approximately 800 tonnes of mercury released to the air, and 1200 t released to land and soil.[211] Artisanal gold mining supports, and is in turn supported by, illicit production and trade of mercury.[212] Mercury may also be released by commercial gold processing, and non-ferrous metal processing (less than 250 t per year).[211]

The Minamata Convention requires that signatory nations develop National Action Plans around the use of mercury in artisanal gold mining, including "Steps to facilitate the formalization or regulation of the artisanal and small-scale gold mining sector".[209] Certification schemes for artisanal miners such as Fairmined align with the Convention, requiring participating miners to reduce or eliminate the use of mercury.[113] However, the uptake of Fairmined by mining communities has been limited, with three certified organisations in Colombia and two in Peru as of end 2020. Fairtrade's Gold standard[112] requires miners to abide by local laws pertaining to mercury, but otherwise does not align with the Minamata Convention. Instead it "recognises the difficulties in eliminating the high risk chemicals mercury and cyanide in mineral recovery", and offers an "Ecological Premium… on top of the Fairtrade Premium for [miners] who chose to eliminate mercury and cyanide altogether".[112] Fairtrade list just three different organisations, all in Peru, as certified artisanal miners.[213]

Figure 2: Estimated mercury release associated with artisanal gold mining and processing.



Source: From Evers et al. 2016.[210]

2.5 Waste

The total volume of tailings produced is increasing over time (doubling every 20–30 years) and the size of individual tailings storage facilities are increasing, as lower grade deposits are mined and processed

The mining and processing of metal ores generates large volumes and masses of waste, with an estimated 100 billion tonnes of solid waste per year from metal and mineral production.[214] A tonne of rock mined may ultimately yield a few kilogrammes of metal — and in the case of precious metals such as platinum and gold, as little as a few grams of metal. Waste derived from rocks will likely never leave a mine site. Underground mines may backfill waste material, but open pits rarely do so. As metal prices fluctuate, and patterns of demand change, mine wastes may become economic, and old dumps reprocessed for their remaining metals.

Tailings are an important class of mine waste. Tailings are produced during mineral processing – ore is crushed to a fine grain size, and the valuable metals and minerals are concentrated into a smaller volume for further processing (such as smelting). The unwanted portion is called the *tailings*. They are commonly a wet slurry of fine-grained rock, water and solvents used in processing. Disclosures to the Mining and Tailings Safety Initiative in 2019 revealed a minimum of 45 billion cubic metres of tailings currently in storage facilities around the world (a figure that will exclude non-tailings wastes, tailings deposited in rivers and seas, and tailings stored in abandoned facilities).[215] Tailings storage volumes are dominated by producers of copper, gold and iron ore.[216] The total volume of tailings produced is increasing over time (doubling every 20–30 years) and the size of individual tailings storage facilities are increasing, as lower grade deposits are mined and processed.[216] Tailings are perhaps the most voluminous of the various wastes from mining and mineral processing, and tailings dams or storage facilities are amongst some of the world's largest engineered structures.[217]

Metallurgical extraction techniques, such as smelting, generate waste in diverse forms. Some solids are captured in filtration and flue-cleaning processes to reduce harmful emissions (see Section 2.). Whilst metallurgical wastes are much lower in volume than the mine wastes, they may be much more concentrated in potentially harmful substances (such as mercury and cadmium). Metallurgical wastes may be shipped around the world for further processing to recover metals such as gold and platinum. A number of metals recovered from these wastes are 'critical' (see Section 1.2). Tellurium, bismuth and rhenium are almost exclusively recovered from metallurgical waste.

Quantification of wastes, in terms of either volume or detailed chemical analysis, is difficult. Many of the wastes never leave the sites on which they are produced, and so are not recorded for shipping, handling or treatment; those that are transported may be defined by the primary metal they were associated with — but not with full chemical analyses on shipping manifests and import logs.

Environmental, social and public health Impacts of mine waste

Mining and mineral processing wastes are typically impounded on site, as they are often too voluminous to transport to off-site disposal facilities. The wastes thus contribute to the land-use footprint of mines (see section 2.1) — and may even be the largest part of the footprint — and pose a long-term risk in terms of contaminated land. There may be little regeneration of soil, vegetation or functional ecosystems on waste because of persistent contaminants. Key contaminants are lead, mercury, cadmium, nickel, chromium and arsenic, on the basis of their widespread occurrence, toxicity (including chronic health effects, cancer, and foetal / developmental impacts), and ready uptake by plants, animals and people.[200,202] Other substances may be problematic at specific sites — including copper, selenium, radioactive metals such as thorium, zinc, cyanide, acids, and persistent organic pollutants.[144,218–221]

Table 2 Notable tailings dams disasters

Event	Impacts	Source
Vale's Córrego do Feijão iron ore mine, Brumadinho, Minas Gerais, Brazil, 2019	12 million m^3 material released. 270 deaths. Contamination of 300 km riverways. Damage to infrastructure including railways. Livestock and agricultural losses.	222–224
Samarco's Germano iron ore mine, Mariana, Minas Gerais, Brazil, 2015	Dam collapse released 50 million m^3 material. Largest tailings failure to date. 13 dead. Short and long term ecosystem impacts over 600 km of Rio Doce river. Then-President Rouseff described it as "worst environmental disaster in the history of Brazil"	225–228
Imperial Metals' Mount Polley copper and gold mine, Quesnel Lake, British Columbia, Canada, 2014	17 million m^3 water and 8 million m^3 tailings released. CAN$70 million clean up costs (~£40 million). Short term negative effects on ecosystems and salmon spawning grounds; potential for long term impacts.	229,230
Ok Tedi copper and gold mine, Papua New Guinea, 1984–2013	Landslide during the construction of the tailings dam led to a switch to tailings disposal (90,000 tonnes per day) into the Fly River, and consequent impacts on water quality, fisheries, and adjacent land over 1000 km of river. Landowners sued the miner in 1994, with settlement in 1996 of ~$113 million.	136,140,231
Aurul's Baia Mare gold mine, Romania, 2000	Dam failures released 100,000 m^3 cyanide-contaminated water into the Someș river, impacting water quality downstream into the Tisza river (Hungary) and the Danube (affecting Bulgaria and what is now Serbia) over 2000 km of the river catchment. Hungarian authorities estimated 1000 tonnes of dead fish were recovered from the Tisza.	134,232

> The failure of tailings dams and release of their contained waste has resulted in industrial disasters with significant loss of life, and degradation of landscapes.

Mine waste poses a physical risk to near mine communities and landscapes. The failure of tailings dams and release of their contained waste has resulted in industrial disasters with significant loss of life, and degradation of landscapes.[137] On average there are at least five significant tailings dam failures per year, and since 1960 at least 2375 people have lost their lives in tailings disasters.[217,233]

Tailings dams remain a risk after mining has ceased, but most (~90%) accidents occur when they are in active use.[234] Tailings in closed or abandoned impoundments may become more stable over time as minerals lock together.[235] Failures at older impoundments are dominated by flooding and overtopping.[234] Such events are often associated with snowmelt, heavy rainfall, or extreme weather events,[234,235] and in some regions will become more likely and severe as a consequence of climate change.

The 2019 disclosures to the Mining and Tailings Safety Initiative showed that 10% of tailings facilities included in the compilation have reported a stability issue, with reported issues increasing as dams get taller, up to 100 m, then decreasing for dams above 100 m, perhaps reflecting greater engineering expertise involved in those structures, and more modern construction.[216] There were more stability concerns reported for larger dams by contained volume.[216]

Tailings management and reduction

The recent Global Industry Standard on Tailings Management (GISTM) has specified clear requirements for miners on the design and monitoring of tailings storage facilities. The GISTM organises a number of requirements under a series of 'Principles', that include design, operation and monitoring for the minimisation of risk for all phases of the storage facilities lifecycles, including closure and post-closure.

A previous UNEP report on tailings[236] made recommendations that riverine tailings disposal should be banned, and that 'upstream' style dam design should be avoided because of its heightened risk of failure,[216] but these were out-of-scope for the final GISTM and bans were not implemented.

Alternative methods of tailings management to the disposal in dams include 'dry stacking', where the water content in the tailings is reduced prior to disposal. This is an important method for reducing net water consumption of mines, particularly in arid climates, and leads to more stable tailings that need less long term monitoring and stabilisation action.[237] They do need additional safeguards against dust generation, and are more costly than conventional dams [237] (notwithstanding catastrophic failures and associated liabilities). Despite the technologies for dry stacking and other reduced-water tailings facilities being known since the late 1960's, the number of sites using this method has remained steady at just 3–6% of all tailings storage facilities.[216]

In-situ mining (or leaching) involves the injection of solvents into volumes of ore, dissolution of targeted minerals, and the recovery of metal-bearing solutions at the surface for processing.[238] Selective mining by in-situ leach methods would dramatically reduce the solid waste and tailings, and decrease the surface footprint of a mine. In-situ mining is already applied to a small number of deposit types, and there are proposals to recover lithium from naturally-occurring geothermal brines in Cornwall. In-situ mining for other metals remains a research frontier, as there are significant challenges in identifying suitable solvents, and controlling their flow and recovery (and minimising losses) during leaching.

2.6 Social impacts

Mining has a complex relationship with society; mined resources are essential for food production, infrastructure, health, sanitation, transport and energy. However, mining can negatively impact the health, wellbeing, safety, prosperity, and culture of communities.

Mining has a complex relationship with society; mined resources are essential for food production, infrastructure, health, sanitation, transport and energy. However, mining can negatively impact the health, wellbeing, safety, prosperity, and culture of communities — particularly those living close to mines, smelters and refineries. Marginalised people, including those of indigenous cultures, are often the most disproportionately affected by these impacts.

Through the concept of the 'social license to operate', mining companies, their investors and the governments that authorise and regulate mining, are increasingly being made accountable to local communities, NGOs and activists, and consumers. This social licence includes agreement and negotiating with communities and their representative decision makers, and often leads to co-development of facilities and infrastructure including hospitals, schools and indirect employment opportunities. Mining has an important role in leading development in otherwise underfunded and underdeveloped areas, and can have positive impacts on the communities, beyond employment.[239]

Artisanal and small-scale mining

Artisanal and small-scale mining (ASM) contributes less to the flow of raw materials than commercial mining, but for some metals up to 25% of supply may come from ASM,[240] and 9 out of 10 livelihoods in mining are in ASM. There are negative associations with ASM too — environmentally reckless mining practices, unsafe work environments, and human rights and labour abuses all occur. The upscaling and mechanisation of mining, including by the arrival of commercial mining operations, may not alleviate these issues, and indeed may complicate them further.

Estimates suggest 40.5 million people engaged directly in artisanal and small-scale mining (ASM) in 2017,[240] and the World Bank estimates that there are more than 100 million workers dependent on ASM (including mineral processing activities and work in support of mines and mining communities).[241] Compared to commercial mining operations, women are a much greater proportion of the workforce, making up around 30% of miners[242] and 50% of the 'indirect' workforce.[243] Worldwide more than 2 million children work in association with ASM.[243]

ASM workers and communities are at risk of exploitation, in terms of child labour and modern slavery.

Data and statistics on ASM are generally poor. The World Bank consider that the data gaps associated with ASM are a barrier to effective decision making and addressing the issues within the sector.[244]

The legal right of landowners to extract minerals from their property varies between countries; for example, fully permitted small-scale mining is found in the USA and Canada. However, ASM is more commonly associated with developing economies, and is widespread in Latin America, Sub-Saharan Africa and across Asia. Artisanal and small-scale mining includes:

- Fully legal and authorised activities, with participants having legal title to the minerals they extract;
- Unlicensed miners who operate at varying risk of enforcement or eviction;
- Illegal and illicit miners who extract minerals that have been licensed to others (typically resulting in tensions between commercial mining operations and authorities); and
- Miners (including forced labourers) who extract minerals to finance criminal, terrorist and militia activities.[212,245,246]

Artisanal miners may be migrants, moving between mine sites as resources are exhausted.[247] Miners move internationally, and often illegally — estimates suggest that more than 70% of artisanal miners in South Africa are undocumented migrants from neighbouring countries.[248] Commercial mining activities may encourage migration (akin to ‘gold rushes’), and the growth of artisanal mining around commercial sites may lead to a large indirect footprint of environmental and social impact related to the mine; minimising tension between ASM and commercial miners is often prioritised over minimising the cumulative environmental impacts.[5] ASM drives migration as it offers access to a cash economy for workers that may be unable to find employment in other sectors, including those that have been displaced from land and agriculture.[249]

ASM workers and communities are at risk of exploitation, in terms of child labour and modern slavery. Some ASM operations exploit human labour to provide finance for criminal activities and conflict. The minerals most commonly associated with such operations are referred to as ‘conflict minerals’, and include tin, tungsten, tantalum and gold (3TGs).[250] The role of non-state armed groups in the Democratic Republic of Congo and its production of tantalum and more recently cobalt have been a particular driver behind national and international legislation around conflict minerals and supply chain scrutiny. The 2010 US Dodd-Frank Act, OECD Due Diligence Guidance,[251] previous UK guidance[252] and the 2021 EU Conflict Mineral Regulation[253] are all motivated by human rights abuses in ASM-produced 3TGs.

Women make up a significant proportion of the ASM labour force. In many cases there are gendered roles within ASM— with men involved in earthworks and extraction, and women used for sorting, separating and processing of minerals. Women’s roles vary regionally, according to cultural norms;[254] in some cultures ASM empowers women, placing them in important roles for the wealth of communities. The formalisation of ASM, or the arrival of commercial

It is increasingly seen as a component of the exploration and feasibility stages to obtain a 'social license to operate' from host communities.

mining operations often leads to net reduction of jobs, and often this loss of work affects women disproportionately. The roles of women in ASM shift with formalisation, as the roles women take become enshrined in laws either directly or indirectly, such as through the award of licences to men.[255] Women in mining communities may resort — or be forced into — sex work[242] and hence be at greater risk of violence[256] and diseases such as HIV/AIDS; policies that drive women out of mining may actually exacerbate this.[257]

There are tensions between commercial miners and artisanal miners; when commercial operations begin work in areas that are already subject to small-scale and informal workings, the artisanal miners may lose their only source of income, and be displaced from the land.[240,258] Whilst commercial miners have legal rights to the land and minerals, artisanal miners may consider themselves as having traditional rights that are poorly represented in legal frameworks. Formalisation is often concerned with legal tenure over the land and mineral rights, rather than protecting livelihoods, and competition for mineral rights with commercial operators exacerbates conflict, rather than remedying it.[259] Routes that allow artisanal miners to formalise and legalise their operations may be overly bureaucratic, inaccessible for the miners and hence ineffective.[260] In some regions, permits are easier to obtain, but there is poor compliance with the conditions of those permits, including environmental practice.[261]

Communities, culture and indigenous people

The mining sector has taken greater account of the views of host communities in recent years. Although the local area to a mine may benefit from employment, economic input and wider infrastructure development, they are also the most impacted by the environmental changes caused by mining, and are at risk from accidents such as tailings dam failures. Local communities may resist the development of mining operations early in the project lifecycle — it is increasingly seen as a component of the exploration and feasibility stages to obtain a 'social license to operate' from host communities.[262,263] In some jurisdictions, this is through the planning process, but in areas where local communities have little sway in decision-making, campaign, protest and social media allow them to apply pressure to investors, central governing bodies and to the reputation of the miners, in some cases leading to the loss of finance or permission for projects.[264–266]

Operational mines become important parts of communities, beyond the employment opportunities they offer. Towns and cities grow around mines, and through their longevity (more than a century for the world's largest mines) they become inextricably linked to the culture and community of their surrounding areas. Mines have infrastructure and services that support the workforce, and increasingly mining companies provide facilities such as schools and hospitals. This has come under scrutiny — there is a perception that the services provided by the mining company replace those that would be expected from the state, and the host communities receive no net compensation to offset the impacts of mining.[267,268]

The consequences mining may be felt more keenly by indigenous communities, with loss of traditional land and access, loss of livelihoods and impacts on heritage and spiritual sites.

The benefits of the arrival of mines are often incorporated into 'community development agreements' (CDAs) as part of the formal relationship between mining companies and their host communities and the decision-makers that act on their behalf.[269,270] The CDAs may be a legal requirement of host nation mining laws,[270] but where not legally enforced, they are common — with various reporting schemes including provision for reporting of community schemes (such as SASB).[271]

The development of a mine can lead to population growth due to migration, including the arrival of workers directly employed in mining. It may also lead to economic inequality in communities, with some jobs and businesses benefiting more directly from mining. The benefits and employment opportunities may be strongly gendered, with more and better roles for men as compared to women, and some jobs (particularly skilled and managerial roles) will go to non-residents. The in-migration and inequality can lead to social impacts, including strain on infrastructure and services, competition for housing stock, criminality, substance abuse, introduction and spread of diseases (including HIV), and changes in culture and community structure.[163,272–275]

Indigenous communities may be disproportionately affected by mining. Indigenous people may have weaker representation and participation in decision making processes, and may be disenfranchised from political agencies.[276] The impacts from mining may be felt more keenly by indigenous communities, with loss of traditional land and access, loss of livelihoods (including traditional forms of agriculture and animal husbandry), impacts on heritage and spiritual sites, and changes to traditional communities.[276,277] The benefits of a mine, such as employment, economic growth and access to amenities, are often less accessible for indigenous communities,[278] and in-migration of workers may displace indigenous people and price them out of accommodation and land ownership.[274] Indigenous communities near mines are more likely to suffer the impacts of increased criminality, poor labour conditions, and exploitation [272] (particularly if the mining is artisanal and informal in nature), and the loss of land, access and ecosystem services may have greater cultural and economic impacts on indigenous communities.[276]

The development of a mine can displace communities from their residencies and employment. Towns, farmland and other infrastructure may be moved to accommodate mines and waste piles. Residents were forced from the Romanian village of Geamăna in the late '70s, as the valley in which it sat was to be used for tailings storage from the Rosia Poieni copper mine (Figure 8). The Swedish town of Kiruna is being relocated two miles away from its original location as a result of impacts from the Kiirunavaara mine.[76]

A mining operation can affect sites of cultural significance (see Figure 8).[277,279] Cultural sites may be protected, but as described in section 2, only UNESCO World Heritage Sites are considered no-go areas for exploration and mining (with some exceptions, as noted in Section 2). The cultural heritage of indigenous people may be particularly at-risk of damage and destruction from mining, as sites of importance may not be properly recognised or protected,[280,281] particularly where that cultural heritage is intangible, and its

Figure 8. The village of Geamăna, Romania, has been submerged by the tailings of the Rosia Poieni copper mine.

Photo courtesy of Sergio Bacioiu.

Box 4 Juukan Gorge

In May 2020, Rio Tinto's iron ore operations in the Pilbara, Western Australia, destroyed the Juukan Gorge site. Juukan Gorge contained a cave that was considered to be the only inland site in Australia that recorded human occupation for 46,000 years.[282,283] The site was traditionally owned, and considered sacred, by the Puutu Kunti Kurrama and Pinikura (PKKP) people, and the impact of the Gorge's destruction on them was "was personal and visceral—and a sharp reminder of how vulnerable their culture and heritage are to the imperatives of governments and corporations".[283]

The decision to blast at the Juukan Gorge site was taken in 2012, and various permissions were sought and obtained through the appropriate formal channels with the Western Australian government. However, various mistakes around Rio Tinto's uptake of archaeological evidence, and poor integration between their operations teams and those working on community and heritage management, led to the company continuing with the plans for the site.[284] An inquiry by the Parliament of the Commonwealth Australia found various failings — as well as Rio Tinto's internal processes, it criticised the communication between the company and the PKKP, and the nature of the agreement between them (in that the PKKP had ultimately ceded most of their rights to prevent the destruction of the site, had they been aware of it). The inquiry also described the state and federal legal frameworks around heritage to be "completely inadequate".[283]

In the aftermath of the Juukan Gorge's destruction, shareholders protested the pay awards to the senior leadership team,[285] and investor pressure forced the Rio Tinto CEO and senior executives to resign.[286] New Australian laws for the protection of cultural heritage are being discussed but are not yet implemented.[287] Rio Tinto have revised their internal processes and corporate governance, with pledges to revise and modernise their agreements with indigenous communities, and to increase diversity in management roles by greater recruitment of indigenous Australians.[284]

destruction is a consequence of indirect and community-level impacts on traditions.[281,288] The closure of a mine will impact local communities. The end of operations will lead to loss of jobs, out-migration of workers, and a drop in the economic inputs to communities.[289] The departure of the mining company may lead to significant losses in services such as schools and healthcare. Whilst post-closure planning to minimise social and environmental impacts is common, these plans may not be adhered to, sometimes due to sudden and unplanned mine closure which is not uncommon and a barrier to post-mine rehabilitation. Operating companies may change as the geological resource dwindles, with ownership — and therefore legacy planning — changing hands in the final years of a mine.[289]

Decision-making

Poor representation in decision-making, and in later distribution of mining revenues, have led to tensions at several mine sites continuing throughout their operation. In some cases, the protest has become conflict.

Commercial mining operations require various regulatory permissions to proceed, at all stages of a mine project's life. The authorities responsible for these permissions include local authorities, environmental agencies and central governments. Mining projects can deliver positive benefits at all levels of government in host countries, in the form of taxes and royalties, wider economic stimulation, and mining companies providing services and facilities that would otherwise come from the state.

The environmental and social impacts of mining are more obvious near to the mine, and so authorities must decide how to balance the local impacts against the regional and national benefits. Mines may be developed in the face of intense local opposition. The participation and representation of communities in decisions at local and government level is variable. Indigenous people in particular can be excluded from permitting and planning processes. Poor representation in decision-making, and in later distribution of mining revenues, have led to tensions at several mine sites continuing throughout their operation. In some cases, the protest has become conflict (see Box 5).

Decision makers should seek to balance the positive impacts of mining against the negative consequences, and this leads to an imbalance between the permitting authorities and the mining industry.[163] There may also be a power and expertise imbalance between mining companies and government agencies regarding technical and legal aspects of permitting.[163] These power asymmetries can lead to the development of mining projects at the expense of rural areas, wilderness, and protected areas (through downgrading, downsizing, and degazettement; see section 2.1).

Decision-making bodies and mining companies may not be able to predict the indirect impacts of a mining project. Indirect impacts include the expansion of non-mining industry and land use, and the in-migration of workers. Indirect impacts may be outside the influence of the mining company, and outside the scope of impact assessments. Similarly, the cumulative impacts of multiple mining projects may be poorly captured by both the companies and regulators.

Corruption

Mining can be subject to corruption, with one in five transnational bribery cases being related to the extractive sector (including oil and gas).[290] A quarter of the corruption cases in extractives are related to approvals and permitting.[290] Mining projects depend on a series of local authorisations to proceed, and some parts of the process (such as seeking exploration licenses and mineral rights) are competitive, and decision makers may be illegally influenced, or stand to make personal gain. Corruption in the approval process can lead to reduced transparency in decision-making, poor stakeholder input, reduced accountability, mines that have negative consequences for the local environment and communities, and little to no post-closure planning and remediation.[291,292]

5 Bougainville and Panguna

In 1972, the Panguna copper deposit of Bougainville — at the time part of Papua New Guinea (PNG) — went into production. Approximately 20% of the mine's revenue went to the PNG government — and constituted 17% of the government's income. The mine became a source of tension between the native Bougainvilleans on one side, and on the other: the operating company, migrant workers (both international and from elsewhere in PNG) and the central PNG government. The Bougainvilleans took issue with a number of aspects of the mine — its environmental impacts, the lack of benefits to customary landowners and the unequal distribution of those benefits to local communities, and the transfer of wealth from Bougainville to the central government of PNG. Tensions between the native population and immigrants grew, as did dissatisfaction with the central PNG government, resulting in outbreaks of violence by the late 1980's. The PNG government dispatched security forces to the island, and the escalation led to the formation of the Bougainville Revolutionary Army, violent conflict and attempted secession. The mine closed, and many non-Bougainvilleans left the island; PNG withdrew forces but blockaded the island from 1990 to 1994. The PNG government made various attempts at recapturing the mine and island until 1997, including the attempted use of international private military contractors.[293]

The death tolls given for the conflict range wildly, but conservative estimates suggest 1,000–2,000 deaths directly from conflict;[294] however, there were many more deaths caused by the loss of infrastructure and services including medical care during the conflict and blockade. A truce was called in 1997, and military forces withdrew from the island. An eventual peace agreement was signed in 2001, and resulted in an end to the violence and greater political autonomy for Bougainville, and in a 2019 referendum the island voted overwhelmingly for full independence in future years.[295]

Companies seeking a social license to operate may (legitimately) enter a transactional relationship with local communities, funding amenities and infrastructure — but corruption within communities may see funding and services unequally or improperly distributed.[290] The remainder of corruption cases associated with the extractive sector are in the operational stages of a project, and include misappropriation of funds, embezzlement, favouritism in distributing or procuring contracts, goods and services, bribery, and avoidance of taxes and fees.[290] Petty and chronic corruption is also a serious concern in the artisanal and informal mining sector, with bribery, graft, and patronage used to avoid scrutiny, gain land, extort money and sexual favours and form debt-bondage over labourers; corruption within the supply chain allows for illicit flows of goods and materials into mainstream products and markets, and hence masks large scale money laundering. The approval processes required for legal artisanal small-scale mining are also frequently subject to corruption.[292]

The UK has a number of anti-corruption laws, including those which have international reach for companies that do some of their business in the UK. The UK is also a participant in the Extractive Industries Transparency Initiative (EITI) a standard that requires the release data on the governance of the extractives sector (including financial streams between government agencies and companies). As the UK is dependent on the overseas production and processing of metals, it has an important role in raising international standards to combat corruption, and supporting other countries to strengthen their governance and transparency, and has enshrined this in the Anti-Corruption Strategy.[296]

3 Governance in the mining industry

3.1 Host country regulations and laws

Variability in governance means that a mine may operate entirely to the satisfaction of its host authorities, yet fail to meet what would be considered best practice elsewhere.

The environmental, social and governance (ESG) aspects of mining are controlled by a complex mix of regulation and law in the host countries. Existing legal frameworks cover every aspect of the mining lifecycle – from initial permission to explore and collect samples, through to post-mine remediation and closure. The regulations vary between countries and even within countries. There may be different rules within a given jurisdiction for miners based on what they extract. This variability in governance means that a mine may operate entirely to the satisfaction of its host authorities, yet fail to meet what would be considered best practice elsewhere.

The governance frameworks around mining may also be weak, with institutions in host countries unable or unwilling to enforce or implement regulations.[297,298] Institutions may lack the technical capacity needed to review and regulate mining activities and their environmental and social impacts. They may have inferior legal teams and be out-performed in litigation. Authorities may be financially dependent on mining revenue and thus have weaker bargaining power. Finally, corruption can undermine otherwise appropriate regulatory frameworks. [163,290]

Artisanal and small-scale mining may evade regulations,[248,299] but recent years have seen considerable progress thanks to efforts by US, Canadian, German and Swiss governments; multilateral institutions including the World Bank and United Nations Development Programme; and public-private partnerships such as the European Partnership for Responsible Minerals and the Public Private Alliance for Responsible Minerals Trade, who are investing in responsible mining and sourcing initiatives that are supporting ASM entities to formalise. Poor governance structures mean that many artisanal miners struggle to formalise, gain full license, and hence participate fully in certification and regulation schemes.

3.2 Transnational and market regulations

Whilst local laws govern the mines and the operating companies in-country, transnational schemes seek to standardise operations in different locations, and hence improve protections towards local people and the environment. There are a number of transnational schemes that regulate the mining industry, with threat of legal and financial penalties for breaches. These schemes include various resource reporting codes, and access to market rules.

Resource reporting codes dictate the way that mining and exploration companies release data to markets and investors, particularly with respect to defining resources and reserves. Failure to adhere to codes can be a breach of a publicly-traded company's legal obligations to their listed market. Various codes are available, but are increasingly aligned, aided by CRIRSCO (Committee for Mineral Reserves International Reporting Standards). The United Nations have also introduced a framework for the classification of resources, and are attempting to align mineral and hydrocarbon resources.[300] Resource codes were introduced in response to high profile market frauds involving mineral exploration projects, and their emphasis is on the integrity of the data and interpretation of mineral reserves and resources.

An emergent theme is the incorporation of ESG considerations into the codes, in recognition that ESG is often a defining factor in whether an ore deposit becomes a permitted mine. ESG issues have typically been dealt with 'off-code' and through compliance with local permitting requirements, but the 'responsible reserves' movement is seeing ESG be raised to the same profile as the geoscience and engineering. The European (PERC) and South African Mineral Codes (SAMCODES) have already introduced ESG criteria.

Access to market rules determine whether companies can list on exchanges, and what materials they sell. The most significant of these in the metals sector to date relate to 'conflict minerals', and examples include the US 2010 Dodd-Frank Act and the 2021 EU Conflict Mineral Regulation. These regulations demand supply chain transparency, in terms of due diligence and reporting. Their aim is to reduce human rights abuses in metal supply (particularly in tin, tantalum, tungsten and gold) from areas in which mining funds violence and warfare, including the Democratic Republic of Congo. Emergent laws in Europe will widen the scope to include any minerals, and include all human rights and environmental risks through the 'horizontal due diligence law'.[301] The EU regulations remain fully applicable in Northern Ireland, and the rest of the UK is aligned through the Trade and Cooperation Agreement and continuing compliance with the OECD Due Diligence Guidance that provided the initial impetus to the EU regulations.[251]

Access to market rules include obligations to report on various ESG metrics, including GHG emissions. The UK's Streamlined Energy and Carbon Reporting (SECR) regulations require GHG data release for UK operating companies, or those listed on FTSE / NASDAQ. The Pension Schemes Act 2021[302] requires UK pension funds to carry out due diligence on their investments and release similar data. At present, these mechanisms relate to GHG data disclosure, but impending regulations such as the EU Carbon Border Adjustment Mechanism will link taxation to embedded emissions of metals including steel and aluminium;[303] the UK may introduce similar legislation to better recognise carbon 'embedded' in goods.[304]

3.3 Reporting and certification

The high profile of ESG in mining has led to a growing body of certification and reporting schemes.

The high profile of ESG in mining has led to a growing body of certification and reporting schemes. Many of these come with no legal requirements, but are used by investors in reducing their financial and reputational risk. Compliance with local laws and regulations may not be visible to investors or consumers, and the variability in local laws between jurisdictions mean that compliance might be a poor measure of ESG performance in some cases. The growth of ESG certification schemes is part of a wider trend for more visible best practice, and a 'beyond compliance' approach.

Mining companies may need to report against multiple different standards to meet the demands of trade associations, membership organisations, and investors. *Generic corporate* reporting schemes include GRI, SASB and TCFD, and data are typically reported at a company level, with multiple mines or international operations aggregated. These schemes are not specifically tailored for the mining and mineral processing sector, but sector-specific guidance has been added in the form of supplements by the parent bodies or the ICMM. Reporting against these generic schemes is a common minimum requirement from institutional investors, and some of the company's legal obligations to report to other schemes (such as the UK's Streamlined Energy and Carbon Reporting) can be aligned with the generic reports to reduce the repetition of data collection, compilation and disclosure.

Metal-specific standards are those that have been set by trade associations, and include Copper Mark, the Aluminium Stewardship Initiative (ASI), and the World Gold Council's Responsible Gold Mining Principles (WGC RGMP). The Copper Mark has an expanded Joint Due Diligence Standard for copper, lead, nickel and zinc with respective trade associations of those metals. A number of the metal-specific standards (such as ASI) support alignment along supply chains as they are relevant to smelters and refiners as well as miners. Some standards, such as ASI, allow companies to combine data from multiple sites into a single report. This 'aggregation' simplifies the data for investors, but means that ESG issues at specific sites may not be obvious. Participation in the metal-specific standards (including the Joint Due Diligence Standard) often results in some form of site- or company-level certification, which can be used to demonstrate compliance with other schemes such as the London Metal Exchange's requirements for Responsible Sourcing, and the 2021 EU Conflict Mineral Regulation.

Sector-specific standards include the ICMM Mining Principles, the Responsible Minerals Initiative's Risk Readiness Assessment (RMI RRA), the Initiative for Responsible Mining Assurance (IRMA) and Mining Association of Canada's Towards Sustainable Mining (MAC TSM) standard (for sites in Canada). Sector-specific standards have arisen from trade associations in the mining sector (MAC TSM), and alliances of downstream companies that depend on mined materials (RMI RRA). MAC and ICMM are membership organisations, and members must comply with their standards. RMI and IRMA are voluntary schemes. For the RMI RRA and ICMM Mining Principles, companies report

Corporate-level sustainability reporting has been subject to significant criticism, particularly from the academic community

whether their policies and practices meet or exceed 'industry norms', and disclose data to GRI reporting standards or similar. MAC TSM and IRMA provide ratings for members and participants against various ESG criteria, with IRMA producing comprehensive reports, scores and commentary from independent auditors. These schemes mostly result in benchmarking scores around policy, practice and protocol, rather than a release of raw data. MAC TSM has been operating since 2016, and in the last round of reports, had just over 30 participating companies. IRMA was founded in 2006, but as of 2021 only has two mines that have completed an audit, with four more underway.

Mine and metal-specific schemes often align with other important standards relevant to mining and mineral processing – these include the Global Industry Standard on Tailings Management (GISTM), and UN System of Environmental-Economic Assessment for Water (UN SEEAW). In many cases they link to international laws and treaties such as the UN Minamata Treaty limiting the use of mercury, and the Convention on Long-range Transboundary Air Pollution (CLRTAP).

In late 2020 the ICMM began publishing equivalency benchmarks between its Mining Principles and other standards (to date – Copper Mark, ASI, RMI RRA, MAC TSM, WGC RGMP and the Responsible Jewellery Council (RJC) Code of Practices (COP) 2019 Standard). These equivalency benchmarks highlight where different schemes exceed, meet or fall short of the ICMM Standard, and can be used to cross check where various schemes' criteria are met. As some deposits produce a number of different metals, operating companies may need to meet more than one standard.

Generic corporate reporting schemes, particularly GRI, are well established, and widely used. Much of the data on environmental and social impacts in this POSTBrief have been derived from corporate reports. However, corporate-level sustainability reporting has been subject to significant criticism, particularly from the academic community:

- The aggregation of data to company-level limits scrutiny of poor performance at specific mine sites;[10]
- Some metrics are under-reported or omitted;[11]
- Lack of transparency and consistency on measurement methodologies, and a lack of consistency on units and measures;[12]
- Infrequent and non-standardised reporting of Scope 3 GHG emissions (which may be particularly large for mining companies);[12] and,
- Sustainability reporting on energy has a tendency towards discussing initiatives in research and development, rather than implementation.[187]

Although less well established than the generic schemes, the more specific schemes help to mitigate some of these issues – as schemes that are dedicated to the mining industry they are better positioned to deliver against the key issues of the sector, particularly when considering the increasing alignment between the schemes, the ICMM Principles and standards such as the GISTM. A number of the more specific schemes require site-level disclosure, which avoids the problems caused by aggregation – but even with

More consumer-friendly schemes are in their infancy; emerging examples include the Global Battery Alliance's 'Battery Passport', which will govern ESG reporting and auditing, and embed performance benchmarks into products.

site-specific reporting, important context may be lost. For example, water consumption has more serious consequences in arid locations.

In contrast to the data disclosures of corporate reporting, the industry-specific schemes tend to return benchmark scores, or pass/ fail criteria (such as policies and management systems being in place). Disclosures associated with industry standards provide important insights into the quality of management in a broad range of ESG performance areas, and may be more meaningful to their intended audience than the release of technical data. Details on policies, or underpinning data, may not always be published or made publicly available.

The various disclosure schemes are primarily aimed at investors, and for them to review a company's year on year progress towards more sustainable operations. The newer schemes that offer benchmark scores (such as IRMA) may allow for more direct comparison between companies, but as a generalisation, these schemes are not designed for company-to-company comparison, and because of the deficiencies listed above, are not particularly useful in this way. More consumer-friendly schemes are in their infancy; emerging examples include the Global Battery Alliance's 'Battery Passport', which will govern ESG reporting and auditing, and embed performance benchmarks into products.[305]

Ratings agencies have grown around the sustainability reporting schemes, providing another layer of benchmarking for investors. These ratings agencies do allow for investors to choose 'greener' companies, but also serve to reduce the need for investors to understand the technical details of ESG reporting, whether that is from mining or other sectors. However, ESG ratings agencies fail to converge to agreed scores and rankings (in contrast, there is close agreement between financial ratings agencies).[306–308]

4 Mining and sustainability

4.1 Can mining be sustainable?

For metals used in specific technologies (such as lithium in batteries), rapid decarbonisation of the world's economies will lead to unprecedented increases in demand that cannot be met by anything other than dramatically increased mining.

The term 'sustainable' emerges from general concepts and can mean different things in different contexts (PN-408). Sustainability is usually described as encompassing three dimensions of human-natural systems – social, environmental and economic,[309] with a common definition of sustainability meeting the, "needs of the present without compromising the ability of future generations to meet their own needs".[310] This concept of sustainability is challenging for the mining industry, as it exploits non-renewable resources.

The predicted patterns of demand across most, if not all, metals show increases driven by growing population and increased per capita consumption of metals (Figure 2). For metals used in specific technologies (such as lithium in batteries), rapid decarbonisation of the world's economies will lead to unprecedented increases in demand that cannot be met by anything other than dramatically increased mining.[311]

Meeting the demand for metals in the 21st century – and indeed up to 2050 – is a challenge for the mining industry. Although current reserves of some metals appear insufficient, reserves are defined by price rather than geological availability, and as a result, our planet's 'stocks' will not be exhausted in the next few decades.[312] A reliable supply of metals will not be limited by the amount of metal in the Earth's crust, but rather:

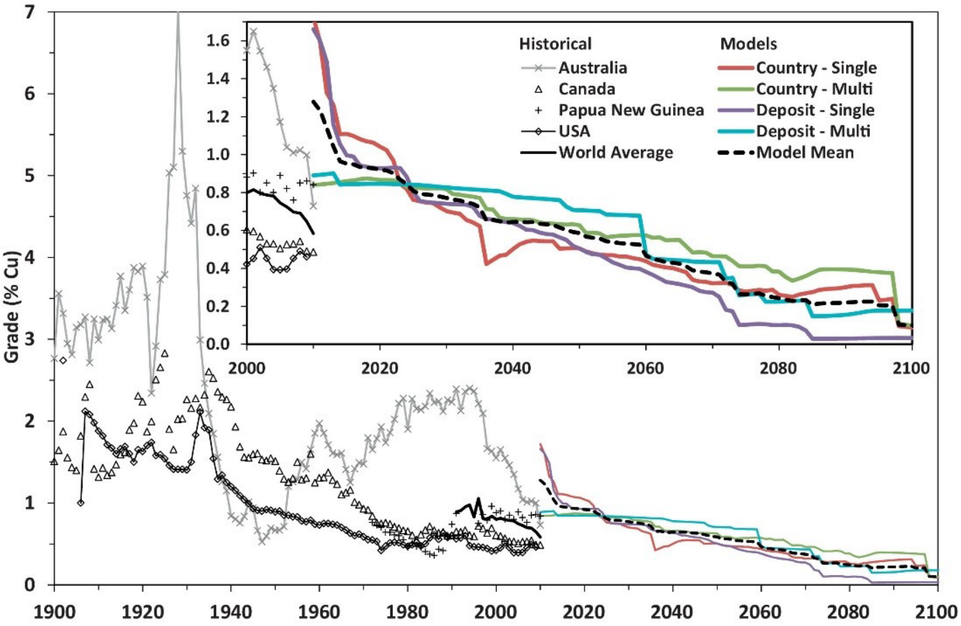
- the long lead times take to find, finance, permit and construct a mine (decades for some);
- geopolitical risks in the supply chain impacting the trade of metals;[312]
- failure of mining projects to obtain their social licence to operate. [35]

The social licence to operate has gone beyond community consent. Regulations and ESG certification schemes have brought the social licence and environmental performance into the relationship between mines and investors, and is beginning to influence consumers.

Modern practice and technology are no guarantee of more sustainable approaches. Some of the case studies discussed in Part 2 of this report include environmental disasters and social conflicts triggered in the last two years, in ostensibly well-regulated countries, by leading companies that have embraced ESG certification. Whilst progress is being made, there is still scope for reducing the negative environmental and social impacts of mining.

Best practice and novel technology may reduce the impacts and risk of accidental failure in mining operations. However, the increased demand for metals, coupled with declining quality (grade and favourable location; Figure 9) of ore deposits means that these pressures on the environment and communities, and consequences of failures will worsen. Mines will inevitably need to use more energy, consume more water and produce more waste.[32]

Figure 9: Historical copper grades produced from mines and projections to 2100 show a decline



Source: From Northey et al. 2014 [32]

4.2 Sustainable development goals and responsible mining

The United Nations developed the Sustainable Development Goals (SDGs) in 2015 as a 'blueprint' for sustainability. The SDGs define a broad set of global ambitions aimed at improving human lives and the environment. Mining has an important role within the SDGs, as a number of them depend on a continued and affordable supply of mined materials – such as infrastructure for clean water and sanitation, and metals and minerals for renewable energy technologies. Achieving the UN SDGs will need more mining, not less. However, mining is also detrimental to some of the SDGs, through pollution, water consumption and social impacts, for example.

Several industry stakeholders use the term 'responsible mining' to better reflect mining's role in sustainable development – mining is a part of sustainable development, but one that comes with environmental and social costs.

An academic review [313] of SDG performance found that increased metal production led to a deterioration in 10% of the 96 SDG indicators, particularly in SDG 3 (Health), SDG 8 (Economic Growth), and SDG 16 (Peace, Justice, and Strong Institutions). Conversely, an ICMM study into the long term performance of 34 mining-dependent countries (those with resources accounting for more than 20% of exports; or resource rents more than 10% of economic output) found improvement on average across 74% of selected SDG metrics.[314] The ICMM selected 41 metrics across the SDGs, primarily focussed on social performance. These studies show the potential for mining to contribute both positively and negatively to environmental and social development in host countries.

Several industry stakeholders use the term 'responsible mining' to better reflect mining's role in sustainable development – mining is a part of sustainable development, but one that comes with environmental and social costs. The activity itself is not sustainable, but reducing the negative impacts allows mining and the metals it produces to support more sustainable development elsewhere.

4.3 The role of innovation

The environmental impacts of mining can be reduced and, in some cases, avoided through the deployment of new technologies. Innovation has allowed the mining industry to keep pace with demand, maintain low prices, improve efficiency, and reduce impacts in key areas such as energy use, emissions, and water consumption.

The mining industry is comparable to a mature manufacturing sector in terms of rate of innovation, but lags behind high-tech sectors.[315] There are a number of barriers to the implementation and diffusion through the mining industry. The variability of metal prices gives mining operations inherent financial risk which is mitigated through conservative approaches. This can be exacerbated in market cycles, as during periods of low prices, cost-cutting may lower social and environmental performance. High capital costs, and longevity of infrastructure (mining and mineral processing facilities often have >10 year operating lifespans) result in "inertia and resistance to change" [316] in both companies and investors. The fragmentation along supply chains means that there is limited diffusion of innovations between miners, mineral processors, manufacturers, the service sector and consultants.[316,317]

Investor pressure to improve ESG performance is an important but relatively recent trend, and in many cases is directly tied to financial performance (through mechanisms like TCFD) rather than wider metrics of sustainability. The competitive nature of the mining sector means that the diffusion of innovation across the whole industry is limited; new techniques, processes and technologies which improve environmental and social performance are still areas in which companies can gain competitive advantage, and in some cases ‘unlock’ new frontiers (such as water-saving measures facilitating mining in arid areas).

The world’s largest ore deposits may be mined over generational timeframes – some for over a century – and likewise, smelters and refineries will have operational lifespans that are measured in decades. Post-closure, these mining facilities may be legacy sites with ongoing environmental impacts for centuries or longer. The ability of old and legacy sites to adopt new technologies and latest best practice will be limited by their ageing infrastructure, and diminishing returns on investment from ore deposits with declining grades and increasing costs. Operational mining facilities include old infrastructure that pre-dates modern concepts of sustainability, and future supply will continue to rely on their production. The deployment of innovation to such sites relies on the ability to retrofit novel solutions, and even still may be capital-intensive.

4.4 Supply chains and consumer choice

The complexity of supply chains in metal production are a barrier to understanding the true environmental and social impacts of their production.

The complexity of supply chains in metal production are a barrier to understanding the true environmental and social impacts of their production – some metals are processed from raw ore to saleable product through a series of companies, potentially across multiple countries. Mineral processors and smelters accept ore from multiple different mines, and export a homogenised product. From a consumer’s perspective, the original source of the material can be almost impossible to verify, and data on the ESG performance of the sources is lost.

Due diligence systems around responsible sourcing have entered legislation (such as the US 2010 Dodd-Frank Act and the 2021 EU Conflict Mineral Regulation) but these have restricted scope in terms of metals covered, source countries, and the ESG factors under scrutiny (they are both focused around human rights abuses and diversion of funds to conflict). Novel supply chain technologies using digital ledgers (including blockchains) might allow for better tracking across more metals, and for that tracking to reach consumers. However, digital ledger technologies are still dependent on the quality of data provided.[318] Audit and verification of the supply chain is a particular challenge in metal supply, given that mineral processing and metal refining remove some of geological ‘fingerprints’ that allow forensic tracing; nevertheless, ‘analytical proof of origin’ tests may support transparency audits of supply chains.[319]

Much of the activity around ESG certification in the mining sector has been aimed at relations between corporations and their investors. There are very few certification schemes that allow consumers to buy metals (or downstream products) on the basis of better ESG performance. Beyond the difficulties of using current ESG certification schemes to compare the performance of multiple companies, many of them do not require measures of ‘intensity’ for key environmental or social metrics, with intensity being the tonnes of CO_2 emitted per tonne of metal produced, the tonnes of water consumed per tonne of metal, etc. The aggregation of data across multiple sites, or the replacement of data with benchmarked scores, prevents the back-calculation of intensity values, and limits the ability of downstream users to carry out life cycle assessments.

Legislation around conflict minerals provides a basis upon which broader ESG metrics and performance might be 'embedded' in products and allow purchasers greater selectivity in which metals they buy. The alignment of certification schemes, such as Copper Mark and the joint Due Diligence Standard, with legal requirements on responsible sourcing, and their adoption by the London Metal Exchange as an indicator of compliance shows a route by which consumers get some minimum assurance on sustainability in metal supply. The LME's proposal to introduce 'Passports' will allow them to embed information from certification schemes and disclosed ESG data into the units of metal traded,[320], and suggests that sustainability reporting and certification schemes could be used more by consumers in the future.

Consumers will ultimately carry the costs of more responsible mining and mineral processing. Those costs may reflect the deployment or retrofitting of new facilities, the greater expenditure on ESG policies, and overheads associated with certification. The declining quality of ore deposits is also likely to result in higher operating costs for miners. Some market-based regulations such as the EU Carbon Border Adjustment Mechanism deliberately use pricing and tariffs to drive ESG performance. The Swiss jeweller Chopard pays a premium of 5–10% for gold from responsible sources (Fairmined and Fairtrade certified producers). [321]

4.5 Regulatory and certification challenges

There remain some key areas in which current regulations and corporate reporting or certification schemes struggle to meet the challenges that mining poses to the environment and society.

There remain some key areas in which current regulations and corporate reporting or certification schemes struggle to meet the challenges that mining poses to the environment and society. Mining projects result in impacts that are not under the direct control of the operating company, and may occur outside the area over which the company holds legal title. As a mine generates further development (such as urbanisation), the cumulative impacts on the local area may be considerably greater than those initially projected. Strategic planning, with detailed regional datasets, are required, yet place significant technical and financial burdens on regulators, and ultimately – the approval of a mining project may still be desirable because of the wider associated development it triggers.

Mining leaves long term legacies on the environment and communities. Most certification schemes and regulators require a post-closure plan for a mine, in order that the operators mitigate some of these impacts before leaving the site. However, the long-term liability a site varies from state to state – Chile for example holds a miner liable for monitoring and management of water quality impacts for five years post-closure, whereas China and the Philippines release companies from liability during decommissioning.[322] The mining operations are often carried out by local, limited legal entities that are dissolved following mine closure, and so even where liabilities remain, there may be no company to be held accountable by regulators or certification bodies.[322]

The regulation of artisanal and small-scale mining is difficult for host nations, as a significant portion of ASM activity is illicit, unlicensed or illegal. Regulations on responsible sourcing (discussed in Sections 2.6 and 1) are one tool to reduce the negative impacts of ASM, but further restricting the economic opportunities of impoverished communities is an emerging 'unintended consequence' of the Dodd-Frank and similar legal mechanisms. Certification schemes for artisanal miners offer a route into the commercial supply chains, but at present schemes such as Fairmined and Fairtrade have had limited uptake as many miners in this sector lack the finances to engage with certification schemes, or the legal title necessary for their participation.

Certification schemes for commercial miners include provisions for their interaction with artisanal miners – it is a recognised source of conflict, and the arrival of commercial mining operations can result in the loss of jobs and income from the informal sector. The debate has shifted from the criminalisation of artisanal mining and seeing them as competitors for the mineral resources, to approaches that look to engage with ASM miners and formalise some of their activities towards mutual benefit. There is a growing body of literature to support commercial miners in their interactions with ASM, but at present little of it is enshrined in regulation or certification, and worldwide the status of ASM miners is subject to local authorities, irrespective of the commercial mining sector's vision of best practice.

Miners that are not dependent on external capital may not need to comply with reporting and assurance. Many of the corporate schemes discussed here are at the interface between miners and their funders – shareholders and investment banks. State-operated mining companies, and those that raise finance privately are not always subject to the same scrutiny, and their accountability may begin and end with local regulators.

4.6 Recycling and resource stewardship

Although the mining of non-renewable metal resource is not sustainable, once extracted, metals are amenable to reuse and recycling. However, current recycling rates are close to zero for many metals (Section 2.1),[13,49] and we are left with environmental and social impacts from both mining and the disposal of end-of-life products. The concept of 'resource stewardship' is that we should better manage metal resources throughout their lifecycle, with more responsible mining operations feeding sustainable products that use metals efficiently, and can be readily repaired, reused or recycled.

A greater emphasis on the recovery of multiple metals from an ore deposit – rather than just those which are most profitable – may reduce the overall number of mines.

Concepts such as the circular economy (PN-646), will be vital in both the short and long term to balance metal supply and demand, and to reduce the true economic, environmental and social costs of mined materials. In a more circular economy, metal demand is lowered by improving the reusability and reparability of devices. Metal supply from end-of-life products could be improved by designing them to ease and increase the separation, sorting and recycling of components. There are further benefits in avoiding waste, which in the case of some metal-bearing products, is itself an environmental hazard.

Our current use of metals is dominated by the purchase and discard of goods; an alternative model of metal use is in services. In this model, metals and products are leased to consumers, rather than sold. This can reduce the costs of products for consumers, as manufacturers do not have to price products for contained high value metals (such as platinum in hydrogen fuel cells), as residual value can be recovered at the end of the lease.[323] Widespread ownership of devices and metals is a barrier to recycling – particularly efficient collection – but the more 'concentrated ownership'[323] under a leasing or extended producer responsibility (EPR) model should improve end-of-life product recovery, repair, reuse and recycling (PN 646).[324,325]

There are other areas in which a move to services rather than private ownership can reduce demand for metals. The conversion of the UK vehicle fleet from internal combustion engines to battery electric vehicles will require "an estimated 207,900 tonnes cobalt, 264,600 tonnes lithium carbonate, 7,200 tonnes neodymium and dysprosium and 2,362,500 tonnes copper".[311] The Committee on Climate Change's Net Zero report already recommends behavioural changes such as increased walking and cycling, and more use of public transport to decrease car mileage,[24] and trends in increased working-from-home may eliminate the commute for many workers. These efforts to reduce transport mileage as part of decarbonisation could be extended to reduce metal consumption through vehicle purchase, and reduce the wider environmental footprint of the UK.

Recycling and resource stewardship are important for improving the overall sustainability of the metals we use, but in the coming decades mining will remain the most important source of the raw materials we need, and particularly for the materials we use in low carbon technologies. The environmental and social performance of mining and mineral processing can improve; the responsible production of metals is an important foundation for sustainability in the UK and beyond.

5 Glossary of useful terms and abbreviations

2021 EU Conflict Mineral Regulation		Legislation aimed at reducing human rights abuses in the supply chains of 3TGs
3TGs	Tin, tungsten, tantalum and gold	Four metals with a significant proportion of supply from the ASM sector; the subject of various pieces of legislation including the 2021 EU Conflict Mineral Regulation
Al	Aluminium	Widely used industrial metal
Alcoa		Multinational mining and mineral processing company
AMD	Acid mine drainage	Acidic water caused by reactions between rocks and water; causes water contamination in mining areas.
Anglo American		Multinational mining and mineral processing company
As	Arsenic	Chemical element, potentially harmful in the environment
ASI	Aluminium Stewardship Initiative	Voluntary scheme. Global non-profit standards setting and certification organisation in the aluminium supply chain
ASM	Artisanal and small-scale mining	Includes informal, illegal and criminal miners
Au	Gold	Precious metal
Bauxite		An ore of aluminium.
BEIS	Department for Business, Energy & Industrial Strategy	
BHP		Multinational mining and mineral processing company
CCUS	CO2 capture and use or storage	

Cd	Cadmium	Chemical element with toxic properties
CDA	Community Development Agreement	Agreements between commercial developers and local communities to define benefits and policies prior to mining.
CLRTAP	Convention on Long-range Transboundary Air Pollution	
Co	Cobalt	Metal, increasingly used in batteries
CO_2	Carbon dioxide	Greenhouse gas, commonly produced by burning fossil fuels
Copper Mark		Voluntary scheme. Assurance framework to promote responsible production practices in the copper industry.
Cr	Chromium	Widely use industrial metal; potentially harmful in the environment
CRIRSCO	Committee for Mineral Reserves International Reporting Standards	A grouping of representatives of organisations that are responsible for developing mineral reporting codes
Criticality		Materials with importance to the economy, national security, or at they are at high risk of supply disruption
CSBI	Cross Sector Biodiversity Initiative	A partnership between extractive industry bodies including the ICMM and investment and development banks including the International Finance Corporation
Cu	Copper	Widely used industrial metal; potentially harmful in the environment
Cyanide		Solvent used in gold processing; potentially harmful in the environment
Defra	Department for Environment, Food & Rural Affairs	
DIT	Department for International Trade	
Dy	Dysprosium	Metal, used in magnets and electric motors. One of the REE
EITI	Extractive Industries Transparency Initiative	Global standard for the good governance of oil, gas and mineral resources.

EPR	Extended Producer Responsibility	A policy approach under which producers are given a significant responsibility for the treatment or disposal of post-consumer product
Equator Principles		A risk management framework, adopted by financial institutions, for determining, assessing and managing environmental and social risk in projects
ESG	Environmental, Social, and Governance	
Fairmined		Voluntary scheme. An assurance label that certifies gold from empowered responsible artisanal and small-scale mining organizations.
Fairtrade		Voluntary scheme. Independent ethical certification system for gold.
FCDO	Foreign, Commonwealth and Development Office	
Fe	Iron / steel	Widely used industrial metal
FTSE		Index on the London Stock Exchange
Ga	Gallium	Metal, increasingly used in semiconductors and solar panels
GHG	Greenhouse Gases	
GISTM	Global Industry Standard on Tailings Management	Voluntary standard that provides guidance to miners on the design and monitoring of tailings storage facilities
Grade		Concentration of economic metal in an ore
Greenhouse Gas Protocol Corporate Accounting and Reporting Standard		Requirements and guidance for companies and other organizations preparing a corporate-level GHG emissions inventory.
GRI	Global Reporting Initiative	Voluntary scheme. International independent standards organization that produces frameworks for sustainability reporting.

Hg	Mercury	Metal; potentially harmful in the environment. Used in the processing of gold in the ASM sector.
Hydrometallurgy		Processing of ore using water-based solvents
ICMM	International Council on Metals and Mining	An international membership organisation founded in 2001 to improve sustainable development in the commercial mining industry
IEA	International Energy Agency	Autonomous intergovernmental organisation
IFC	International Finance Corporation	International financial institution that offers investment, advisory, and asset-management services to encourage private-sector development in less developed countries
IPIECA		A global not-for-profit oil and gas industry association for environmental and social issues
IRMA	Initiative for Responsible Mining Assurance	Voluntary scheme. Certifies social and environmental performance at mine sites
ISA	International Seabed Authority	Intergovernmental body that organizes, regulates and controls all mineral-related activities in the international seabed area beyond the limits of national jurisdiction
Joint Due Diligence Standard		Voluntary scheme. Extension of Copper Mark to Cu, Pb, Ni and Zn.
JORC	Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves	Mineral reporting code. Related to CRIRSCO
LBMA	London Bullion Market Association	International trade association representing the global bullion market
LBMA Responsible Sourcing		Independent audit programme verifies the legitimacy of gold and silver supply chains. Mandatory for members of LBMA and access to London Bullion Market.

		Related to the OECD Due Diligence Guidance
LCA	Life Cycle Assessment	Methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service
Li	Lithium	Metal, increasingly used in batteries
LME	London Metal Exchange	World's largest market for metal (and derivatives) trade
MAC TSM	Mining Association of Canada's Towards Sustainable Mining	Voluntary scheme. Site level programme for mining companies to manage environmental and social risks
Nasdaq		New York stock exchange
Nd	Neodymium	Metal, used in magnets and electric motors. One of the REE
Net Zero Carbon		Strategic plans implemented by various countries (including the UK) to achieve net zero carbon dioxide equivalent emissions by a set date (UK 2050) as part of their commitments to the UNFCC 2015 Paris Agreement
Newmont		Multinational mining and mineral processing company
Ni	Nickel	Widely use industrial metal; potentially harmful in the environment
NI 43-101		Mineral reporting code. Related to CRIRSCO
NNL	No Net Loss	Biodiversity conservation policy. Impacts in one location are offset by remediation of another site.
OECD	Organisation for Economic Co-operation and Development	Intergovernmental economic organisation. Often used as shorthand for nations with well-developed economies
OECD Due Diligence Guidance		Recommendations to help companies avoid purchase of 3TGs with human rights abuses in their supply chain
Ore		Rock with a high concentration of economically valuable metal

PA	Protected area	
PADDD	Protected area downgrading, downsizing, and degazettement	
Pb	Lead	Widely use industrial metal; potentially harmful in the environment
PERC	Pan European Reserves and Resources Reporting Committee	Mineral reporting code. Related to CRIRSCO
Phytoextraction		Growth, harvest and controlled disposal of plant species that accumulate the contaminants
Pyrometallurgy		Processing of ore using high temperatures
REDD+		Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries
REE	Rare Earth Elements	Group of metals used in various technologies including wind turbines and electric motors
Refining		Purification of metals from ores during hydrometallurgy or after smelting
Reserves		The economically mineable part of a Measured and/or Indicated Mineral Resource.
Resources		A concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction
Rio Tinto		Multinational mining and mineral processing company
RMI RRA	Responsible Minerals Initiative's Risk Readiness Assessment	Voluntary scheme. Self-assessment and self-reporting tool for minerals and metals producers and processors to

		communicate their ESG practices and performance.
SAMCODES	South African Mineral Codes	Mineral reporting code. Related to CRIRSCO
SASB	Sustainability Accounting Standards Board	Voluntary scheme. Standards for ESG disclosure and reporting
Sb	Antimony	Metal; potentially harmful in the environment
SDGs	United Nations' 2015 Sustainable Development Goals	A broad set of global ambitions aimed at improving human lives and the environment
Se	Selenium	Chemical element; potentially harmful in the environment
SECR	Streamlined Energy and Carbon Reporting	UK government requirement for mandatory annual reporting and disclosure of energy and carbon information from companies
Smelting		Process of applying heat to an ore to produce a metal (also known as pyrometallurgy)
SO_2	Sulphur dioxide	Atmospheric pollutant
Tailings		Common form of mine waste. Residue from processing of ore
TCFD	Task Force on Climate Related Financial Disclosures	Voluntary scheme (mandatory in UK from 2025). Standards concerning reporting to investors regarding governance, strategy, risk management, and metrics and targets related to climate change risks and mitigation
UN SEEAW	UN System of Environmental-Economic Assessment for Water	Conceptual framework for organizing hydrological and economic information
UNESCO	United Nations Educational, Scientific and Cultural Organization	
UNFCCC	United Nations Framework Convention on Climate Change	

United Nation's Minamata Convention on Mercury		International agreement to control, reduce, or eliminate sources and use of mercury.
US 2010 Dodd-Frank Act		Also known as the Wall Street Reform and Consumer Protection Act. Title XV included requirements for producers using potential conflicts minerals (3TGs) to disclose their supply chain audits, and assess whether materials from the Democratic Republic of Congo are benefitting armed groups.
Vale		Multinational mining and mineral processing company
WGC RGMP	World Gold Council's Responsible Gold Mining Principles	Framework to recognise and consolidate existing standards and instruments under a single framework, including ICMM Principles, OECD Due Dilligence Guidance and EITI
Zn		

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