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Reducing the health risks of the copper, rare earth and cobalt industries

TRANSITION TO A CIRCULAR LOW-CARBON ECONOMY

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Abbreviations and acronyms

ARD	Acid rock drainage
CE	Circular Economy
CO_2, CO_{2e}	Carbon dioxide, carbon dioxide equivalent relative to global warming potential
CRM	Critical raw materials
DRC	Democratic Republic of the Congo
EEA	European Environment Agency
EIA	Environmental impact assessment
E-PRTR	European-pollutant release and transfer register
EU	European Union
EV	Electric vehicle
GDP	Gross domestic product
HRAPIE	Health response to air pollutants in Europe (a review by WHO-Europe for the European Commission)
HREE	Heavy rare earth element
ILO	International Labour Organization
LCA	Life cycle analysis
LCP	Lithium cobalt phosphate battery
LFP	Lithium iron phosphate battery
LMO	Lithium manganese oxide battery
LREE	Light rare earth element
NdFeB	Neodymium-iron-boron magnets
Ni-Mh	Nickel metal hydride battery
NMC	Lithium nickel-cobalt-manganese oxide battery
NOx	Oxides of nitrogen (as NO and NO_2)
OECD	Organisation for Economic Cooperation and Development
OSHA	US Occupational Safety and Health Administration
PM	Particulate matter (as an air pollutant)
RE, REE	Rare earth, rare earth element
SO_2	Sulfur dioxide
SX-EW	Solvent extraction and electrowinning
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
WEEE	Waste electrical and electronic equipment
WHO	World Health Organisation
WTO	World Trade Organization

Executive Summary

This paper reviews the environmental risks to human health associated with the primary and secondary production of copper, rare earth elements (REEs), and cobalt. These metals have been selected based on their growing importance, including for green emerging technologies, such as electric vehicles and wind power, and recognition of the burdens that they may impose on society through the extraction and production process. The paper reviews these effects and considers how a drive for a Circular Economy (CE) that keeps extracted metal working for the economy through actions such as re-use and recycling can help to mitigate them.

Impacts to health and the environment may occur at all stages of the metals production process, from extraction and processing of ores to refining. They include:

- Accidents that cause injury, illness and death to workers, in mining particularly, but also elsewhere in the production process.
- Accidents, such as dam failures, that impact the local population directly, affecting their health, property and the quality of their surroundings.
- Effects of occupational exposures to hazardous substances.
- Health and environmental impacts of air pollutant emissions.
- Contamination of land and water, and associated effects, again on human health and the environment.
- Exploitation of workers, including children in some regions.

It is to be recognised that these risks are not a necessary burden of the metals industries. Profitable metals businesses operate in both highly regulated and less regulated regions. The less regulated industries generate added profit by burdening their workforce, the local population and society more generally with the externalities of their actions.

Numerous life cycle analyses (LCAs) (covering all of the metals considered here) have demonstrated that pollutant burdens are diminished by recycling. LCA has paid less attention tore-use and repurposing of goods that contain metals, but these actions can improve overall system efficiency as an intermediate step prior to (ultimately) recycling. Increasing the efficiency of material use and avoiding or limiting the use of hazardous substances also reduces burdens on society.

Important knowledge gaps are identified, concerning, for example:

- The need for better and more complete data on occupational health risks.

- How strategies for circularising the economy should account for uncertainty regarding the evolution of technologies, for example driven by climate change mitigation, the development of new products and of alternatives for handling waste products and other secondary material streams such as industrial wastes. Flexible strategies may be needed to cope with the varying possibilities for future systems. The potential for institutional and legal barriers to obstruct the most efficient ways forward must be kept under review.

- The lack of expertise in some countries for controlling risks.

- The need to be able to track metals back to their origin, to ensure that supply chains are operated to standards that are ethically acceptable and do not compromise human and environmental health more generally.

Key policy questions are identified, concerning:

- How aware are policy makers of the avoidable harm to health and the environment from current mining and metals processing operations, and of their long-term consequences?

- Are policy makers aware of the concept of the Circular Economy and of its benefits to health, the environment and sustainability of industrial processes, for example through maintaining supplies of critical raw materials?

- How should industrial policies be revised to better exploit the benefits of material recovery? What barriers constrain the market in secondary materials, and how can they be overcome?

- What can be done to better protect workers, particularly those in the "informal" part of the industry? Objectives include the avoidance of exploitative labour practices, including the use of child labour, ensuring that wages properly reflect the value of the work done, the adoption of safe working practices and provision of care for those harmed through their work.

- Are adequate compensation systems in place for individuals and communities who suffer the consequences of poor health and a damaged environment?

- How can best practice for protection of workers, local communities and the environment be more effectively disseminated?

The paper concludes by assessing possible roles for government and industry. Proposed roles for government are as follows:

- Recognising that the extraction and processing of metals, both primary and secondary, can impose significant burdens on society, but that these can be mitigated. Many companies already operate to high standards in the competitive global marketplace, demonstrating the affordability of actions to protect workers and the local environment.

- Enforcing good governance of mining and metals processing activities to ensure that hazards are rigorously controlled.

- Promoting best practice in the metals industry.

- Developing a circular economy strategy that includes systems for improved waste management. Recognise that delaying this action will generate substantial costs of environmental remediation in the near future in addition to the harm being caused at present.

For the metals industries the following actions are recommended:

- Adoption of best practice to minimise exposure of workers to hazardous substances and risks of accidents and to minimise environmental contamination and other risks

- Collaborative working between companies to maximise the quantity of metal gained per unit of ore extracted, with government to establish efficient systems for the collection of recyclable materials and with manufacturing industry to ensure the traceability of supplied metals.

- Investment in R&D for the recycling of novel materials and new applications of materials.

For manufacturing industry, the following roles are envisaged:

- Ensuring that materials are ethically sourced, without exploitation of either workers (including children) or those whose air, land and water are impacted by metal extraction and processing.

- Manufacturing goods that can be disassembled easily to facilitate recycling generally, but specifically to assist the recovery of materials for which supplies are limited.

- Investment in R&D to substitute away from the use of hazardous materials, and minimising their use when substitution is not feasible, and to increase the efficiency of metals use in products.

1. Introduction

1.1. Objectives of this report

The shift to a circular low-carbon economy is likely to lead to numerous important changes in the supply and demand of materials. On the one hand, the transition is likely to increase the demand of specific metals. Examples include rare earth elements (REEs), which are used in a wide variety of low-carbon and energy efficiency technologies (e.g. wind turbines, high strength magnets, lighting and hydrogen fuel cell), or cobalt, for which demand is growing rapidly, especially for manufacture of electric vehicle (EV) batteries. A shift to a Circular Economy will also lead to more efficient usage of resources, leading to much larger recycling rates than those currently observed in both OECD and non-OECD countries.

These structural changes will drive employment reallocation across a number of industries with implications for the types (and levels) of occupational and environmental risks faced by workers and by society more generally. The extraction, separation and refining of the materials that underpin several low-carbon technologies may expose workers and the environment to significant risks. Furthermore, increased reutilisation of metals has both positive and negative implications for the environment and human health. For example, many authors report a substantial reduction in environmental impacts for a number of metals when using secondary rather than primary production processes. However, there is still potential for formal and informal recycling workers to experience unhealthy exposures to various substances and other risks.

This paper reviews the literature on environmental risks to human health associated with the primary and secondary production of copper, rare earth elements (REEs), and cobalt. These metals have been selected based on their growing importance for the global economy, including for emerging technologies, such as electric vehicles and wind power, and recognition of the burdens that they may impose on society through the extraction and production process.

1.2. The Circular Economy

There is no single accepted definition of the Circular Economy (CE). However, different definitions share the concept of decoupling natural resource extraction and use from economic output, hence increasing resource use efficiency. The broadest view of the circular economy and one that has been adopted in earlier work for OECD (McCarthy et al., 2018; OECD, 2019a), is the more efficient use of natural resources, materials and products within an existing linear system. This broad view of the circular economy affects potentially all economic activities, not only those that have a high material use profile. Recycling, as considered here, is only one part of the CE model that extends through product design, production processes, consumption, material, innovation and investment activities.

The concept is receiving widespread interest and support. The European Union, for example, published its Circular Economy Action Plan in 2015[1] and its Circular Economy Package in 2018.[2] These activities cover various actions on both waste management and eco-design, strengthening earlier initiatives. In a review, RIIA (2017) notes activities in many other regions. Examples include:

- The governments in Rwanda, Nigeria and South Africa launching the African Alliance on Circular Economy.
- Multilateral development banks exploring CE with Colombia and Turkey.
- The Indian Resource Panel's action agenda on resource efficiency.
- Promotion of CE in China since 2009.

Against this, progress in many areas is slow, with recycling rates for many metals a small fraction of the quantity used (Table 1.1). Illegal operations, harmful to health and the environment, still occur despite international action through the UN dating back to the late 1980s, through:

- The Basel Convention of 1989 on the Control of Transboundary Movements of Hazardous Wastes and their Disposal[3]
- The Rotterdam Convention of 1998 on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade.[4]

It is also noted that governments still provide significant support for metals producers without balancing this support against the externalities generated by the industry. Tax exemptions and the public provision of finance on concessionary terms are the most common mechanisms in the primary sector, whilst grants and transfers induced by waste management policies are more common in the secondary sector (McCarthy and Börkey, 2018), with the sums involved running into billions of dollars for individual projects. Provision of this finance creates potential for distortion between primary and secondary metal producers. To the extent that this distortion boosts the share of primary output of metal production, it is expected to have negative consequences for overall environmental quality and for health (McCarthy and Börkey, 2018), in conflict with the concept of the circular economy.

1.3. Metals and the Circular Economy

1.3.1. Metals recycling

The OECD's Global Material Resources Outlook to 2060 (OECD, 2019b) projects

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015DC0614

[2] http://ec.europa.eu/environment/circular-economy/index_en.htm.

[3] http://www.basel.int

[4] http://www.pic.int

that global GDP will triple between 2017 and 2060, but that technological developments will help to decouple growth in production levels from the material inputs to production. With respect to primary materials use, metals growth is forecast to grow more rapidly than for non-metallic minerals such as sand, gravel and limestone. The report notes that metals extraction and processing are associated with large environmental impacts. It also finds that recycling will become more competitive compared to extraction of primary minerals, but that the relatively high labour costs for secondary materials use will limit penetration growth of the secondary materials market.

A report from UNEP (UNEP, 2011), considering future opportunities, limits and infrastructure needs for metals recycling, notes the following:

- Global economic growth will stimulate increased use of metals. If emerging economies were to adopt similar lifestyles and technologies as OECD countries, global demand for metals would increase by a factor of between 3 and 9.

  There is an increasing amount of metal in circulation within society, as much as 15 tonnes per person in developed countries. Most of this (98%) is in the form of iron, aluminium, copper, zinc and manganese. Stocks of metal in infrastructure and industrial goods are relatively easy to collect, whilst it is harder to collect material in private hands. Together with the declining quality of ore in terms of its metal content (ores with the highest metal content have been exploited preferentially), this makes end-of-life materials increasingly important as a source of metal.

  Complexity also arises from alloying to give metals specific properties, such as machinability, colour, corrosion resistance and use in high-temperature or high-wear situations. In addition, metals are increasingly used in combination with other materials, such as plastics and ceramics.

- Recycling of metals generates multiple benefits, in terms of:
  - the value of recovered metal
  - the value of energy saved in metal production
  - the reduction in the risk of metal scarcity to mitigate supply risks and geopolitical uncertainites
  - various health and environmental benefits, from reduced mining activities and reduced emissions from metals manufacture.

Despite these benefits from environmental, economic and social perspectives, current recycling rates at a global level are still rather low for most metals. High scrap-recycling rates seem to exist only for metals mainly used for simple (bulk) products, such as iron and nickel in carbon- and stainless steels, for precious metals (mostly jewellery and similar simple products) and for lead in batteries. Recovery rates are illustrated in Table 1.1 and Table 1.2 from UNEP (2011). There is no indication of significant changes in recycling rates in the intervening period at a global level.

Table 1.1. Recycling rates for metals.

	Elements
>50%	Al, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Nb, Rh, Pd, Ag, Sn, Re, Pt, Au, Pb
>25 – 50%	Mg, Mo, Ir
>10 – 25%	Ru, Cd, W
1 – 10%	Sb, Hg
<1%	Li, Be, B, V, Ga, Ge, As, Se, Sr, Zr, In, Te, Ba, Hf, Ta, Os, Tl, Bi, REEs

Source: UNEP, 2011.
Note: Elements not included in the table were either not considered by UNEP or no data was found. The rare earth elements (REEs) include Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu.

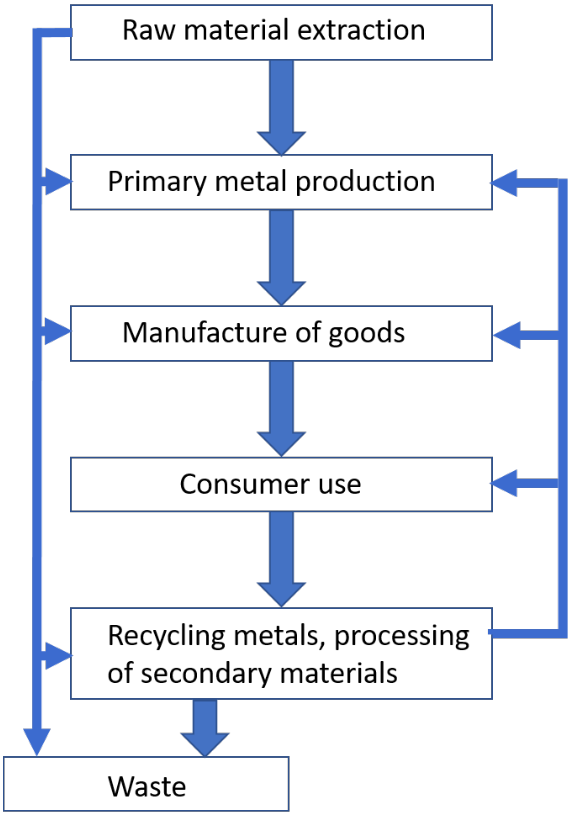
Table 1.2. Recycled content of metals.

	Elements
>50%	Nb, Ru, Pb
>25 – 50%	Mg, Al, Mn, Fe, Co, Ni, Ge, Mo, Rh, Pd, Ag, In, W, Pt, Au, Hg
>10 – 25%	Be, Ti, Cr, Cu, Zn, Ga, Cd, Sn, Sb, Ta, Re, Ir
1 – 10%	Se, Zr, La, Ce, Pr, Nd, Gd, Dy
<1%	Li, As, Y, Ba, Os, Tl, Sm, Eu, Tb, Ho, Er, Tm, Yb, Lu

Source: UNEP, 2011.
Note: Elements not included in the table were either not considered by UNEP or no data was found. Elements in red font are considered in this report.

Figure 1-1 illustrates material flows in metals industries. It indicates the extensive interactions that exist between primary producers, recyclers and other players in the supply chain (the “industrial symbiosis” present within the metals sector). It is acknowledged that the extent of these interactions will vary by region, but there is a growing global trade in secondary materials leading to reductions in waste generation. Recycling operations are not restricted to relatively pure post-consumer waste, but to secondary materials generated throughout the supply chain. Slags and sludges from primary producers contain valuable metal but at too low a concentration, or in the wrong form, for the “primary” production processes. Some recyclers have developed their business models to take advantage of these materials. They have taken the concept of resource recovery beyond metals to generate other useful secondary materials from the recycling process, including sulphuric acid and building aggregates, with the objectives of generating profits whilst minimising their own waste streams.

Figure 1-1. Illustrative material flow for the metals industries



For some parts of the material stream, there are no markets and so it is inevitable that waste will be generated. This will include some fractions containing significant quantities of hazardous substances, such as cadmium and arsenic. A clear advantage of the recycling process is that these materials can be concentrated down to a much lower volume of waste, reducing demands on hazardous waste storage. The concentration of the harmful components also reduces risks during handling, transport and storage.

1.3.2. Characteristics of metals significant to recycling processes

Metals rarely occur in nature in pure form. Individual ores may contain several metals that need separation: cobalt, for example, is mainly extracted from copper or nickel ores. Some of the co-occurring metals are useful in themselves, though some are not and some, such as arsenic and cadmium, are hazardous, leading to the generation of hazardous waste streams.

Unlike materials such as glass, plastics or paper, metals do not degrade through the recovery process. The markets for final metals demand high standards for purity (often that must be met by virgin and recycled material alike). Key to the recycling process is thus the ability to attain appropriate standards of purification: without this, recovery will not be economic and recovery systems will fail. This has been complicated by trends in metal use over time. For most of human existence, society has exploited a relatively small suite of metals (iron, cupper, zinc, tin, lead and a few precious metals). These tended to be used in relatively pure form. Since the start of the 20th century, however, many more metals have been exploited, as knowledge about their properties and technologies has developed. This trend is especially notable in the electronics sector, where 40 or more different metallic elements may be used in an item such as a mobile phone (Rohrig, 2015). CEC (2018) provides the following list of elements used in a smartphone:

- Battery: Lithium, cobalt, copper, iron
- Electronics: Silicon, copper, gold, silver, tantalum, nickel, praseodymium, gadolinium, terbium, dysprosium, neodymium, tin, lead
- Screen: Silicon, aluminium, sodium, potassium, indium, tin, rare earths
- Case: Aluminium, iron, magnesium, nickel

From the perspective of the CE, this creates several difficulties:

- Many metals are used in only trace quantities in articles.
- Efficient collection systems for electronic goods are lacking in many parts of the world, limiting the quantity of material available for recovery.
- Economically efficient methods are as yet unavailable for recovery of all useful metals.

As of 2018, it is estimated that only 20% of global electronic (e)-waste is recycled each year. Despite 66% of the world's population being covered by relevant legislation, 40 million tonnes of e-waste is either placed in landfill, burned or illegally traded and treated in a sub-standard way. This results in the loss of valuable and critical raw materials from the supply chain and can cause serious health, environmental and societal issues. There is particular concern over illegal shipments of waste to developing countries that lack the capacity for safe processing of material, leading to damage to both health and the environment.[5]

Over time, improvements in technology seem likely to continue to increase the complexity of articles in terms of the elements that they contain, assuming that the trajectory of recent years is maintained. At the same time, the quantity of precious and other metals in each article (though perhaps not in total) may well decrease, as manufacturers develop methods for improving the efficiency with which the more expensive elements are used. To illustrate, the Mitsui Mining and Smelting Company has developed a catalyst for diesel engines that replaces platinum with silver (it is understood that this has yet to enter production), whilst Honda have developed an improved 3-way catalyst for gasoline engines that reduces rhodium use by 50%, overall use of precious metals by 22% and cost by 37% (Els, 2013). These trends are driven by a mix of high costs and uncertain conditions for primary supplies of some metals. A consequence that is particularly relevant here is that metal recyclers dealing with complex materials continually need to adapt to new challenges, and that forecast

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[5] http://www.weee-forum.org/international-e-waste-day-0.

growth in the use of some metals may not materialise. Policy makers have recognised the long-term economic importance of certain materials, metals in particular, and have developed listings of "critical raw materials" (CRMs) taking account of risks to the economy of supply shortages, substitutability, recycling rates and the concentration of production in countries that are judged to be politically unstable (Coulomb et al., 2015). The EU's list of CRMs has grown over time as further information on the economic importance and supply risks of materials has become apparent. Its first list in 2011 contained 14 CRMs, the second in 2014 contained 20 and the most recent, from 2017, contains 27. This increase reflects market trends, and methodological improvements, for example taking better account of recycling practices. The US list is longer, containing 35 critical minerals. The European and US lists are presented in Table 1.3 by way of illustration. It is noted that critical mineral strategies exist elsewhere also (e.g. Australia, China and Japan: Barteková and Kemp, 2016). The strategies vary in form between countries to reflect national economic perspectives and domestic availability of mineral resources.

The lists considered in the table demonstrate that supply risk is not limited to a small number of materials, and that metals feature very strongly on the list, particularly when noting that some of the rows in the table, for example covering rare earths and platinum group metals, contain multiple substances. This highlights the importance of the Circular Economy for the metals sector and all other sectors dependent on it.

UNEP (2011) illustrates recycling potential through "the metal wheel" that describes the affinity of metals for one another, and the likelihood of recovery. Most recovery is linked to metals used alongside copper, lead, nickel, tin and zinc. In contrast, most of the metals contained alongside aluminium and iron, such as the rare earths, are currently lost, requiring the use of recovery systems that are not currently widespread.

Another characteristic of metals that underlines the need to consider recycling is that the quality of available ores, in terms of their metal content, is fast declining: society has naturally focused on extraction from sources that are both rich in metal content and easy to exploit, and is now moving to lower grades of ore in locations where extraction is more difficult. The quality of copper ores in terms of metal content, for example, has fallen from about 4% in 1900 to 1% now, though this is in part a function of improvements in metallurgical technology that enable the exploitation of lower grades (West, 2011). One consequence is that mining activities have grown substantially in scale, beyond simple growth in demand for metals. Another consequence is that per unit of production, the footprint of mining operations has grown substantially, with the decline in ore quality for copper leading to the generation of four times as much waste as previously.

Table 1.3. EU and US lists of critical raw materials

	US	EU	Uses
Aluminium (bauxite)	✓		Many
Antimony	✓	✓	Batteries, flame retardants
Arsenic	✓		Preservatives, pesticides, semi-conductors
Barite	✓	✓	Cement and petroleum industries
Beryllium	✓	✓	Alloys for aerospace and defence
Bismuth	✓	✓	Medical and atomic research
Cesium	✓		Research and development
Chromium	✓		Stainless steel and other alloys
Cobalt	✓	✓	Rechargeable batteries and superalloys
Coking coal		✓	Steel industry
Fluorspar	✓	✓	Manufacture of aluminium, gasoline and uranium fuel
Gallium	✓	✓	Electronics, including LEDs
Germanium	✓	✓	Fibre optics and night vision appliances
Graphite (natural)	✓	✓	Lubricants, batteries and fuel cells
Hafnium	✓	✓	Nuclear control rods, alloys and high temperature ceramics
Helium	✓	✓	MRIs, lifting agents and research
Indium	✓	✓	LCD screens
Lithium	✓		Batteries
Magnesium	✓	✓	Furnace linings for manufacture of steel and ceramics
Manganese	✓		Steelmaking
Natural rubber		✓	Automotive and other applications
Niobium	✓	✓	Steel alloys
Platinum group metals	✓	✓	Catalysts
Phosphate rock		✓	Fertiliser
Phosphorus		✓	Fertiliser, steel
Potash	✓		Fertiliser
Rare earths	✓	✓	Batteries and electronics
Rhenium	✓		Lead free gasoline and superalloys
Rubidium	✓		R&D in electronics
Scandium	✓	✓	Alloys and fuel cells
Silicon metal		✓	Alloys and electronics
Strontium	✓		Pyrotechnics and ceramic magnets
Tantalum	✓	✓	Electronics, mostly capacitors
Tellurium	✓		Steelmaking and solar cells
Tin	✓		Protective coatings, steel alloys
Titanium	✓		White pigment and metal alloys
Tungsten	✓	✓	Wear resistant materials
Uranium	✓		Nuclear fuel
Vanadium	✓	✓	Titanium alloys
Zirconium	✓		High temperature ceramics

Sources: USID, 2018, European Commission, 2017.

Notes: Coulomb et al. (2015) for OECD also consider bentonite, borate, clays, copper, diatomite, feldspar, gold, gypsum, iron ore, limestone, magnesite, molybdenum, nickel, perlite, selenium, silica sand, talc and zinc.

2. Environmental health risks associated with primary and secondary metals production

2.1. Production chains and induced hazards

Figure 2-1 provides a generic illustration of the burdens generated at different stages during primary and secondary metal flows through to the production of finished metal, based on review of the documents listed below in the references. Transport emissions are added as applying throughout the production chain. The extent of damage associated with activities will vary from location to location, depending on the regulatory environment, the extent to which regulations are enforced, the behaviour of operators and other local factors. The fact that more burdens are listed against primary production should not be taken as an indication that primary production is necessarily more damaging than secondary at this point: key to the overall outcome for health and the environment is the legislative framework in place at any location and the extent to which it is applied.

2.2. Hazards associated with mining, and collection of secondary materials

The process of primary metal production starts with mining while collection of waste is the first step for secondary material production. The hazards associated to these two phases are described in more detail below.

2.2.1. Hazards associated with mining

The extraction of metal ores involves the extraction of large quantities of material using either human labour or heavy machinery from surface or underground mines, creating physical hazards for workers. Further hazards may arise through the use of explosives or chemical agents, and exposure to dust containing hazardous substances in mines. Underground mining is often associated with a high accident rates through the collapse of tunnels and flooding, often with limited potential for recovery. Declining ore quality (as discussed above) in the most accessible resources and advancing mining technologies are opening up the possibility of mining much deeper underground than previously[6].

Effective regulation has a substantial effect on the safety record of mining operations. From the literature survey carried out here it is apparent that the highest risks at ore extraction sites are in low-income countries where regulation is weakest.

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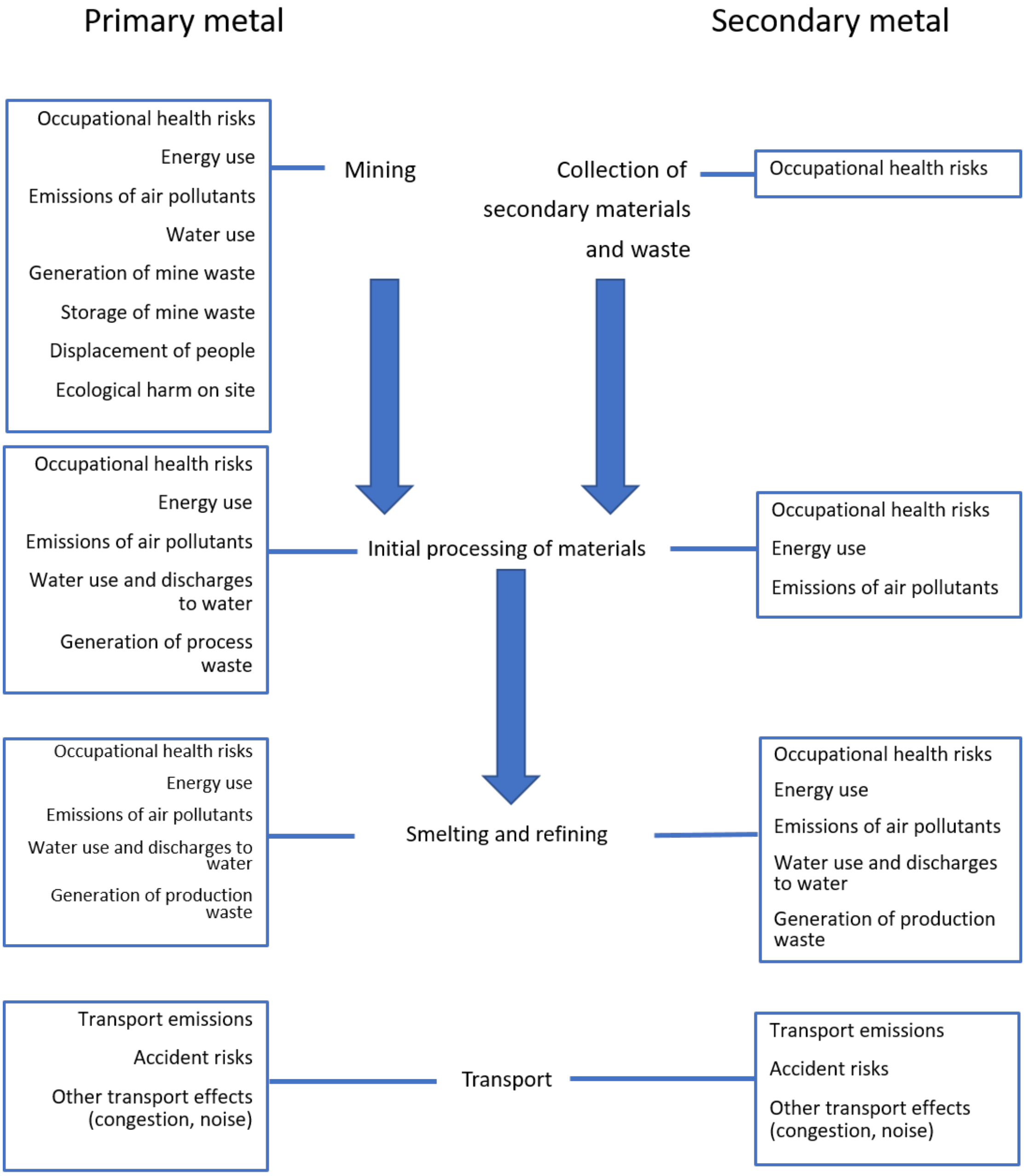
[6] https://www.riotinto.com/ourcommitment/spotlight-18130_22504.aspx

Figure 2-1. Burdens generated during primary and secondary metal flows through to production of finished metal.



A detailed account of the possible effects of metal mining in low-income countries is provided by Emmanuel (2018), considering impacts on workers and the surrounding population for gold mines in Ghana. The outcomes reported are seen in many areas and are not specific to either Ghana or gold mining. Accidents can be on a major scale: Emmanuel notes an accident in a "galamsey" (informal) pit in Ghana in 2010 that killed an estimated 150 workers. In addition to the risk of accidents, Emmanuel lists pneumoconiosis, asbestosis, silicosis and lung cancers. He also reports increased levels of malaria, colds, skin diseases, diarrhoea and buruli ulcers in workers and those living close to mines. Mining activities have also been linked to the spread of HIV/AIDS as a result of elevated levels of the sex trade in mining towns. There are also, of course, examples of well-run mining operations in low income countries that have much-reduced impacts in comparison to the informal sector.

Issues related to labour migration are highlighted in a report by the International Labour Office (Coderre-Proulx et al, 2016). They found limited availability of data on the number and working conditions of migrant labourers. The report finds that temporary foreign labour, especially low-skilled workers, are, generally, more vulnerable to the risks of employer exploitation than members of the permanent work force. The report also argues for better controls of artisanal mining to protect workers and raises concerns about the trafficking of women and children to mining areas. Coderre-Proulx et al. (2016) document links between HIV and transient mine workers in the Zambian Copperbelt region, with many women being trafficked from Zimbabwe on the trucks that service the mines.

International comparison of mining accident data is difficult given that published data sets often do not distinguish between activities. The country with the highest number of reported fatalities from accidents in the category 'mining and quarrying" in the ILO (2018) dataset (which covers all mining activities, not only metals extraction) for the period 2009-2017 is the United States averaging 144 "mining and quarrying" deaths per year. National statistics for mining alone in the United States indicate a much lower figure, 28 for 2017, of which 15 were in coal mining and 13 in other mining (MHSA, 2018). Inspection of activity data on the extractive industries in the United States shows most activity in US "mining" relating to extraction of sand and gravel, and stone (NIOSH, 2018).

Next on the ILO list is Russia (128, but with data reported for only one year) and Turkey (117). There are some notable absentees from the list, including China and India. Simple totals of fatalities are a very crude indicator of mining risk as they do not account for the number of workers or productivity, let alone permit risks of different mining activities to be evaluated (the importance of which seems to be shown in the US data cited above). Even where data are present, they are likely to be incomplete for many countries, with accidents in artisanal mining widely under-reported, especially where such activities are illegal. Given that the risks of mining activities are so well recognised, it is disturbing that it remains difficult to compare data across countries data in a way that provides a thorough overview of the sector. Such a dataset would facilitate dissemination of best practice in a more targeted manner than is currently possible.

Damage to land in Ghana has made previously fertile land unusable for farming, for example through the dumping of mine debris at the surface and the presence of mine shafts and trenches. Kuemmerle (2011) notes that displaced farmers in Ghana often obtain alternative land by clearing forest or renting land. In the latter case, farmers often cultivate smaller farms, reducing incomes. Some start working in mining operations, legal and illegal.

Acid mine drainage, or acid rock drainage (ARD), is another major problem linked to the mining industry, occurring particularly when ground with a high sulphide content has undergone major disturbance. The discharge of affected waters spreads both acidity and toxic metals into the environment. In the metals industry, copper mines are a major source, given that one of the most commonly mined copper minerals, chalcopyrite, is sulphide based. Effects may continue for many years: UNEP (2004) reports that Roman mine sites in the UK continue to generate acid drainage nearly 2 000 years after mining ceased. In well-regulated regions, mine companies are required to control the problem for as long as is necessary, even after mines are closed for production. This is not, however, the case everywhere. Canada's Mine Environment Neutral Drainage (MEND) Programme[7] was set up in response to growing liabilities associated with ARD, in the order of CAD 2-5 billion. Investments of CAD17.5 million over 8 years has reportedly reduced liabilities by CAD 400 million.

CEC (2018) finds that the mining sector accounts for one third of pollutant releases reported to the North American (Canada, Mexico, USA) Pollutant Release and Transfer Registers[8], amounting to 1.67 million tonnes. Regulation across the region has done much to limit impacts on workers, those living in surrounding areas and the environment and in all three countries covers exploratory activities and remediation of contaminated sites.

A particular problem around the world is that the enforcement of regulation (to the extent that it exists) is often weak for small scale "artisanal" mining activities or to other larger-scale illegal mining operations that provide some of the worst illustrations of health and environmental harm associated with the industry. Article 7 of the Minimata Convention (UNEP, 2017) on mercury requires Parties to the Convention to reduce and where feasible eliminate the use of mercury in gold extraction, though the process continues.

There are also signs of progress. The Chinese government, for example, has sought to consolidate production of rare earths through six state owned mining companies, in part at least through recognition of extensive contamination associated with their mining and processing of ores. China considers that illegal activities drive down global prices for rare earths and have made it impossible to cover the costs of environmental contamination (Reuters, 2019). However, problems of illegal activity remain, a decade after the initiative started.

2.2.2. Hazards associated with secondary materials collection

The collection of secondary materials follows a similar pattern. In regions with high levels of regulation burdens are typically limited. Much of that burden is linked to transport operations, taking waste from primary metal production, manufacturing and consumers to sites for processing. Given a global market for scrap and secondary materials, there is potential for transport burdens to become significant as material is

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[7] http://mend-nedem.org/default/

[8] The scope of the North American PRTR differs to the European equivalent coordinated by the European Environment Agency. Comparison of the relative importance of sectors between the two systems is not straightforward.

moved over large distances. Dealing with large quantities of material there is always risk of accidents in the workplace, and exposure to hazardous substances that are present in some of the materials.

However, in regions with a low level of regulation the burdens of secondary material collection can be significant. Waste pickers on dumps and landfills in low- and middle-income countries face a number of risks relating to physical hazards, and exposure to hazardous chemicals and infectious wastes (Gutberlet and Uddin, 2017). Another example concerns shipbreaking (Box 2-1).

Box 2-1. Occupational hazards in shipbreaking

Risks to shipbreaking workers arise from working with heavy equipment in enclosed spaces and through exposure to excessive noise or chemicals. Numerous hazardous substances are present in ships, including asbestos, PCBs (polychlorinated biphenyls), lead and other toxic metals, CFCs and oils (OSHA, undated). The International Labor Organization (ILO, undated) note that a ship of average size contains up to 7 tonnes of asbestos. The majority of scrappage yards have no waste management systems or facilities to prevent pollution, leading to significant damage to the surrounding environment. Muhibbullah and Molla (2014) provide an environmental impact assessment of shipbreaking in Bangladesh and note significant impacts on health and the environment. The International Maritime Organization (IMO) developed the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships in 2009[9]. However, by June 2019 only 12 countries had ratified the convention which only enters into force once at least 15 states have done so. Japan is the only Asian country to have ratified, although most shipbreaking activities (>90%) in the world are undertaken in Asia. Bangladesh, India and Pakistan account for 80% of the market for commercial ships (Saul and Jessop, 2018). Alternative approaches to regulation have been brought in, with ships being added to the definition of toxic waste under the Basel Convention and development by the EU of a listing of approved ship recycling facilities[10].

2.3. Hazards associated with initial processing of materials

2.3.1. Initial processing of materials for primary metals

Initial processing of ores typically takes place at or near mine sites, given the volume of material involved. Ores are crushed and metals extracted using a leaching solution. Many of the substances used to extract metal are highly toxic such as cyanide, sodium hydroxide, lead and mercury. Routine use of these substances can lead to high levels of contamination of the environment, rendering water supplies dangerous and reducing the quality of farmland and ecosystems.

In addition to the "routine" contamination associated with ore processing (emissions of air pollutants, controlled release of treated waters), treatment wastes have been involved in a number of high-profile accidents. The 2019 disaster at the Brumadinho mine in Brazil, where an estimated 12 million m^3 of mine waste were released

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[9] http://www.imo.org/en/OurWork/Environment/ShipRecycling/Pages/Default.aspx

[10] https://ec.europa.eu/info/news/shipbreaking-updated-list-european-ship-recycling-facilities-include-six-new-yards-2018-dec-06_en

following failure of a storage dam, is a timely reminder of the potential damage associated with mining operations. At least 186 people are reported to have died in the accident, and many more remain missing. There is also widespread contamination of the environment, impacting on human life, agriculture and ecosystems. The accident followed from one in 2015, the Mariana dam disaster, also at a Brazilian iron ore mine, run by the same company, in which 60 million m^3 of waste were released, and 19 people died. In the earlier incident, the force of the mudflow also destroyed 1 469 hectares of forest and killed a large quantity of fish. Hundreds of people were displaced, and water shortages were experienced in affected communities. Other notable accidents involving dam failure occurred in Romania in 2000 and Hungary 2010. The Baia Mare gold mine spill in 2000 released 100 000 m^3 of wastewater that was heavily contaminated with cyanide from gold mining. The 2010 disaster at the Akja alumina plant led to the release of 1 million m^3 of residues left after the refining of bauxite with sodium hydroxide to dissolve aluminium oxide. Ten people died, 150 were injured and 40 km^2 of land were affected. Released material was highly alkaline.

2.3.2. Initial processing of materials for secondary metals

In well-regulated environments, the initial processing of secondary materials will have little impact on the health of workers, the public or the environment. Activities will include sorting of materials, perhaps separation of individual components from electronics, shredding or grinding, and mixing of materials. The complexity of operations is dependent on the materials used. Relatively pure wastes, such as copper pipe, will need little treatment, whilst complex wastes, such as electronics, will need more.

However, there are extensive reports of processing of e-waste in particular in unregulated environments. The World Health Organisation highlights a number of risks from a systematic review of the health consequences of exposure to e-waste (Grant et al., 2013):

- Emissions associated with burning cables to eliminate plastic coverings and generate pure copper scrap

- Exposure to harmful substances contained in electronic wastes, including lead, cadmium, chromium, brominated flame retardants and PCBs

- Generation of toxic by-products

- Risk of injury from dismantling appliances.

Of added concern is the exposure of children to these activities, either as they occur in a child's home, or through use of child labour. Grant et al. (2013) identify a number of plausible health outcomes associated with exposure to e-waste, including change in thyroid function, changes in cellular expression and function, adverse neonatal outcomes, changes in temperament and behaviour, and decreased lung function. Most studies showed increases in spontaneous abortions, stillbirths, and premature births, and reduced birthweights and birth lengths associated with exposure to e-waste. However, there was also inconsistency between studies and Grant et al. (2013)

recommended that more, well designed, epidemiological studies were needed. The papers that were included in the review are largely, possibly entirely, associated with places where standards of recycling and public protection have been low, rather than well-managed e-waste sites.

2.4. Hazards associated with smelting and refining

2.4.1. Primary materials

Like the activities identified above, the hazards associated with processes at smelters and refineries are in large part a function of the regulatory environment and its enforcement. Facilities may vary greatly in their health and safety records, emissions to the environment per unit of material produced, water use and waste generation depending on where they are located.

The majority of energy use in metals production occurs at the refining stage. Burdens associated with mining represent about 1% of global energy consumption, whereas those associated with production of iron and steel and non-ferrous metals make up a further 6% of global energy consumption (IEA, 2018). Efficiencies in the sector therefore have significant potential to contribute to a greening of the economy, with consequences for emissions of greenhouse gases and local and regional air pollutants. McCarthy and Börkel (2018) note that the primary metal production process in particular is highly energy intensive and that producing finished metals from mineral ore can require as much as two orders of magnitude more energy than doing so from metal scrap. However, Alova (2018) highlights the growing business case for using renewable energy technologies, especially wind and solar, in the extractive industries. Alova concludes that timely exploitation of these technologies will require an enabling policy environment featuring a competitive energy market and adequate energy infrastructure, to overcome current challenges and support the synergies between the development of the mining and renewable energy sectors.

2.4.2. Secondary materials

A characteristic of secondary materials in metals production is that they can contain significant quantities of toxic metals, such as cadmium and arsenic, for which uses are strongly declining in response to legislation. The presence of significant amounts of such metals can lead to wastes being considered hazardous and subject to additional controls. An advantage of secondary metal production is that by separating out desired metals and other useful materials, volumes of hazardous waste can be much reduced. They will still require disposal, but the smaller quantities involved will have much reduced demand on available storage capacity. However, the presence of hazardous substances in the waste stream raises potential for exposure of workers and local residents.

2.5. Comparative life cycle analysis of metals

Analysis by Nuss and Eckelman (2014) provides estimates of the carbon intensity of 63 metals, including all of those considered in this report. Results are shown in Table 2.1. Analysis, focusing on production in 2008, was based on existing life cycle inventory datasets and further information from literature search. It is noted that, given the co-production of metals (e.g. cobalt with copper), results are sensitive to the approach taken to the allocation of impacts, whether by the mass of metal or the economic value.

Table 2.1. Estimated cradle to gate greenhouse gas emissions from global production of cobalt, copper and rare earth elements for 2008.

	Tonnes metal	Tonnes CO_2eq	tCO_2eq/t metal
Cobalt	57 290	475 000	8.3
Copper	17 660 000	54 500 000	3.1
Rare earths			
Scandium	10	57 100	5 710
Yttrium	13 940	210 000	15
Lanthanum	25 810	284 000	11
Cerium	34 180	440 000	13
Praseodymium	4 979	95 500	19
Neodymium	17 880	314 000	18
Samarium	2 397	142 000	59
Europium	299	181 000	605
Gadolinium	2 436	114 000	47
Terbium	321	95 200	297
Dysprosium	1 879	112 000	60
Holmium	394	88 900	225
Erbium	1 060	51 600	49
Thulium	179	116 000	649
Ytterbium	844	105 000	124
Lutetium	164	147 000	894

Source: Data from Nuss and Eckelman (2014)
Note: Allocation of impacts to co-produced metals is based on economic value.

Despite having the lowest carbon intensity of the metals shown here (see final column), copper provides the highest total contribution to global warming in these estimates because it is produced in by far the largest quantity. Results for other metals in the analysis by Nuss and Eckelman (2014) indicate that global copper production ranks fourth amongst the metals in terms of its carbon footprint, generating about 1.6% of the total burden from metals. Production of iron and steel dominates, contributing over 70% to the total, with aluminium second, contributing 11%. Conversely, scandium has the highest carbon intensity, but given the low quantities produced makes the second lowest contribution to overall emissions.

2.6. Comparative analysis of primary and secondary metal flows

Carbon foot-printing has provided a focus for comparison of the performance of primary and secondary metal flows. Grimes et al. (2008) provide data on the carbon footprint of metals recycling relative to primary metal production based on life-cycle analysis, taking account of variation in energy supplies at a global level (Table 2.2), with savings for in excess of 90% for some metals.

Table 2.2. Carbon footprint of metals from primary and secondary production.

	Primary, kt CO_2/t metal	Secondary, kt CO_2/t metal	% reduction
Aluminium	383	29	92%
Copper	125	44	65%
Ferrous metals	167	70	58%
Lead	163	2	99%
Nickel	212	22	90%
Tin	218	3	99%
Zinc	236	56	76%

Source: Grimes et al., 2008.

Factors influencing the size of the emission savings are varied and include physical factors (e.g. melting point of the different metals), the energy sources used in different countries and the purity of waste materials used for recycling. The analysis of Grimes et al. is thus useful as a general guide, though there may be situations where the difference in carbon footprint at least is not so significant.

3. Environmental risks to human health associated with the primary and secondary production of copper, rare earth elements (REEs), and cobalt.

3.1. Key insights

This section summaries the key findings of literature on environmental risks to human health associated with the primary and secondary production of copper, rare earth elements (REEs), and cobalt. These metals have been selected because of their increasing importance in the global economy, including for green technologies such as electric vehicles and wind power. The key findings are summarised in the tables below while a detailed discussion is provided in the dedicated chapters in the appendix.

Table 3.1. Summary of the burdens and impacts of primary and secondary copper production.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for 'artisanal' mining. Substantial reduction in risk through effective regulation and mechanisation.	Not applicable.
Initial processing, production of copper concentrate	Emissions of SO_2 to air, with potential for significant health damage. Emissions of acids, metals and other pollutants to water, contaminating land and drinking water. Spills of acid, again contaminating land and drinking water. Controllable via regulation.	High risk where informal processing is carried out, with particular concern over the dismantling and processing of e-waste, including the burning of insulation from wires. Emissions include lead and dioxins. This may affect workers, their families and neighbours. Substantially lower relative to primary production in well-regulated environments, given the reduction in SO_2 emissions.
Production of refined copper	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Discharge of metals and some organics to waters. Emissions can be closely controlled, both to air and water.	Similar types of impact to those from primary production of copper. However, the process is more efficient and leads (all else being equal) to reduced inputs, by around 60%.
Transport	Impacts will be dependent on transport distances. These are generally significant given the regions where copper is produced and major markets.	Generally low, given that secondary materials will need to be moved for disposal if not recovery. However, may become large through international trade in secondary materials.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, ore quality and fuels used, especially for power production. Quantified health impacts related to air pollutant emissions are estimated at EUR 730/t of copper under a low emission scenario driven by effective regulation of emissions and renewable energy use, and EUR 46,000/t of copper under a high emission scenario with limited emissions regulation and high fossil energy use. Impacts other than air pollutant effects are not included in these figures.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production. Quantified health impacts related to air pollutant emissions are estimated at EUR 260/t of copper under a low emission scenario driven by effective regulation of emissions and renewable energy use, and EUR 8,000/t of copper under a high emission scenario with limited emissions regulation and high fossil energy use. Impacts other than air pollutant effects are not included in these figures.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

Table 4.2. Summary of the major burdens and impacts of primary and secondary production of rare earths.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for illegal and unofficial mining. Potential for significant release of dusts, thorium and uranium. Substantial reduction in risk possible through effective regulation.	Not applicable.
Processing of ores and secondary materials	Significant use of caustic agents and solvents, potentially contaminating land and drinking water. Controllable via regulation.	High risk where informal processing is carried out, with particular concern over the dismantling and processing of e-waste. This may affect workers, their families and neighbours. Substantially lower relative to primary production in well-regulated environments.
Smelting	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Emissions can be closely controlled, both to air and water.	Similar types of impact to those from primary production. However, energy and other savings of around 50% seem achievable. This figure may rise as recycling technology advances assuming that recycling innovation keeps pace with developments in battery technologies.
Transport	Very largely dependent on proximity of operations to the Chinese centres of rare earth production for the foreseeable future.	Potentially significant given that there will be possibly few centres equipped for rare earth recovery, leading to the movement of secondary materials over significant distances, dependent on any barriers to trade that may exist.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, ore quality and fuels used, especially for power production.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment and advances in knowledge and optimisation of recycling technologies for the rare earths. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

Table 5.3. Summary of the major burdens and impacts of primary and secondary production of cobalt.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for illegal and unofficial mining with particular concern over. Substantial reduction in risk possible through effective regulation.	Not applicable.
Processing of ores and secondary materials	Significant use of caustic agents and solvents, potentially contaminating air, land and drinking water. Release of arsenic compounds from some cobalt ores. Controllable via regulation. Energy use, generating emissions to air.	Lower burdens relative to primary production in well-regulated environments.
Smelting	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Emissions of the pollutants most damaging to health can be closely controlled, both to air and water. Greenhouse gas emissions are controllable partly through efficiency measures and more extensively through the use of low-carbon/carbon-free energy alternatives.	Similar types of impact to those from primary production. However, savings of energy are achievable, though some evidence indicates that these are likely to be modest, less than 10%. This figure may rise as recycling technology advances.
Transport	Significant transport distances from DR Congo to main processing sites in China.	Potentially significant given that there will be possibly few centres equipped for reprocessing new types of battery, leading to the movement of secondary materials over significant distances.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, the type and quality of ore used. and fuels used, especially for power production.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment and advances in knowledge and optimisation of recycling technologies for cobalt. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

4. Discussion

4.1. Examples of existing good practice in the global metals industry

There are many examples of good practice already in the metal industries with relevance to reducing burdens on human health. Several of these are also aligned with the concept of the Circular Economy reflecting more efficient use of resource, for example:

- Development of safe working practices, protecting workers from physical, chemical and other risks. This is illustrated by the decline in rates of accidents and occupational disease in some countries.

- Development of efficient systems for the collection of wastes and other secondary materials. The most efficient example identified here concerns the collection of automotive batteries for recovery of lead: it is anticipated that the same mechanisms can ensure recovery of the growing quantity of Li-ion batteries provided that sufficient capacity is available to reprocess them.

- Development of innovative techniques for the cost-effective recovery of metals from secondary materials. In the case of lead-acid batteries this comes close to a “closed-cycle”, where almost all material is collected, and the recycled content of new batteries is very high. In the case of consumer electronics, such as mobile phones, innovation has established cost-efficient methods for extracting metals present at only trace quantities.

- Development of “industrial symbiosis” between companies, trading secondary materials to gain maximum value from the metals that they process and to minimise the generation of waste.

- Control of emissions to a high standard. This was highlighted most clearly in relation to emissions of SO_2 from copper production (Table 3.4), where the best performing plant had emissions of SO_2 per unit of copper produced that were 90-99% lower than other facilities.

- The adoption of high standards for site-remediation when metal extraction and processing is finished.

All of these measures are effective in controlling risks to human health, by ensuring a safe working environment, by reducing pollutant releases in the short term and by reducing the accumulation of hazardous materials that pose a growing burden for the future.

4.2. Examples of existing bad practice in the global metals industry

Just as there are examples of good practice in the global metals industry, there is also bad practice, leading to unnecessary burdens on health and the environment, as the following examples show:

- Unregulated "artisanal" extraction practices in various countries, where workers have minimal protection against accidents, and exposure to dusts and harmful substances. In relation to the materials considered in this paper, particular concern remains over conditions for workers involved in cobalt extraction in DR Congo.

- Limited protection of workers against physical and chemical risks at some official mining and processing sites.

- Excessive releases of hazardous air pollutants that can be controlled with cost-effective abatement techniques.

- Direct dumping of other hazardous substances to the environment, contaminating towns and the countryside.

- Accidental failure of dams, leading to the inundation of villages, rivers and farmland. In many such cases, contamination is severe and long-lasting, leading to the abandonment of land and property.

- Low recycling rates and the export of electronic equipment to countries that lack the capacity to safely process them. This includes much waste of materials, including some identified as "critical raw materials". Evidence from the LCA studies considered in this report demonstrates that low recycling rates also increase energy demand and the pollution associated with it and other risks both to workers and the general public for all of the metals considered here. Risks are heightened by the continued use of hazardous substances in goods destined for disposal or recycling: these could be better targeted to be designed out of products.

4.3. Comparing primary and secondary metals production systems

Life cycle analysis demonstrates that there are significant advantages in recycling metals. Analysis tends to be more focused on energy use and associated emissions, but the demonstration of efficiencies to be gained through better exploitation of secondary materials will apply more generally.

The limitations of LCA need to be understood:

- The technique deals only with material flows and does not factor in additional burdens, for example, accidents.

- LCA work tends to deal with hazard rather than risk and hence does not factor in the potential for hazards to be managed efficiently. Data availability is substantially worse where regulation is poor.

- LCA does not typically extend to a quantification of impacts beyond the use of characterisation factors that enable comparison of the hazard of different substances. An example is the use of global warming potentials to indicate which GHGs are most potent.

Data from Grimes et al. (2008) and Jin et al. (2016) indicate roughly a 60% reduction in environmental burdens through recycling for copper and rare earths respectively. Dewulf et al. (2010) reported slightly lower (50%) savings for cobalt recycling, though Ragei and Winfield (2019) reported more modest savings, in the order of 10%. Significant variability reflects differences in the systems considered and the recycling routes followed (whether to pure metal, to alloys, etc.), but all of the LCAs identified in the course of this work conclude the same thing, that recycling is more efficient with respect to pollutant burdens than virgin metal production, and in most cases substantially so.

LCA results indicate that a significant part of the aggregate burden of metals production is linked to emissions of air pollutants and greenhouse gases from energy production. Results will be sensitive to the assumption of the current energy mix associated with metals production and future developments for the energy sector, recognising growing pressure for decarbonisation. Improved efficiency in the sector (as in any other) will facilitate the move towards decarbonisation by reducing total energy demand.

Future trends are also important in other ways. The burdens of mining and ore processing will increase in future as the quality of ore (the fraction of ore made up of valuable materials such as copper, rare earths and cobalt) declines further. This increases the amount of material that needs to be processed, increases the quantity of acids and other materials used for processing, and leads to exploitation of materials in more difficult locations, for example, deeper underground. This will widen the gap in performance between primary and secondary production.

4.4. Knowledge gaps

Much of the information used in this report can be improved on through the use of more thorough and systematic approaches to data collection, for example the collation of data on accidental and other health risks of mining and other industrial activities. Here, however, we focus on some important areas where knowledge gaps are significant determinants of current and future performance in the industry:

- The significant changes in the energy sector that are required for climate change mitigation affect all three of the metals and groups of metals considered in this report as they are critical to the generation, transmission and storage of electricity. Future demand for the metals will be a function of many things, including global population and economic growth and technical advances. Alternative scenarios should be developed in order to better understand the potential for shortages of these metals to inform ways of meeting demand. Given estimates of demand growth, and the time taken to develop effective waste management infrastructure and technical capacity, this should be considered as a matter of urgency to avoid the shortage of critical materials and the price shocks that would follow.

- The pace of technological change produces uncertainty about the way in which goods at end-of-life will most efficiently be processed. In some cases, the optimal solution may be recycling, in others, it may be repurposing. Flexible strategies may be needed to cope with the varying possibilities for future systems, and the potential for barriers to obstruct the most efficient ways forward must be kept under review.

- The lack of expertise in some countries regarding safe operation of sites, the benefits of recycling and the running of efficient waste management practices. This can be overcome by knowledge sharing and capacity building.

- It is important to be able to better trace metals back to their origin, to ensure that supply chains are operated to standards that are ethically acceptable and do not compromise human and environmental health more generally. The importance of this for primary production in the metals sector has been highlighted by reference to the use of child labour in cobalt extraction. For secondary production, similar concerns apply for communities and individuals carrying out basic processing of electronic waste.

The presence of knowledge gaps does not undermine the wider conclusions of this report.

4.5. Key policy questions

This report has identified significant benefits associated with the production of copper, rare earth metals and cobalt from secondary materials and wastes. It has also found that the impacts of primary production vary substantially from case to case, depending on a variety of factors ranging from the quality of ores to the effectiveness of governance. The following key policy questions are identified:

1. Are the benefits of reusing equipment such as automotive batteries and recycling metals, in terms of reducing harm to health and the environment and ensuring resource security, recognised sufficiently by governments and industry to ensure greater efforts are made in the future to work within a more circular economy structure? Whilst these benefits are not adequately recognised, there remains the risk of a lack of action from government and industry alike.

2. Are the burdens of primary metal production understood by government? There is a substantial literature on these burdens and on best practice designed to avoid risks to health and the environment. Given that businesses operating to the highest standards remain competitive on the international market, what prevents adoption of best practice?

3. How should industrial policies be revised to better exploit the benefits of material recovery? For example:

    a. Are there barriers to the trade in secondary materials that constrain recovery rates? How can these be avoided without increasing risks to health and the environment, noting that international obligations on shipment of hazardous waste shipments are still not rigorously observed?

    b. Can traceability of materials through the supply chain be improved to enable manufacturers to account for the burdens of production in their purchase decisions?

The development of new industrial policies can take advantage of existing models from regions that have already begun adoption of Circular Economy strategies. These will need to be adapted to best fit the precise situation of additional regions, but much of the basic framework is likely to apply quite generally.

4. Given that recycling, carried out to a good standard and with appropriate safeguards in place, is recognised as significantly reducing impacts on health and the environment, how can barriers to increasing recycling rates be overcome?

5. What can be done to better protect workers, particularly those in the "informal" part of the industry? Objectives include:

    a. The avoidance of exploitative labour practices, including the use of child labour,

    b. Ensuring that wages properly reflect the value of the work done,

    c. The adoption of safe working practices,

    d. Provision of care for those harmed through their work.

A difficulty here lies in ensuring that those that such a policy seeks to help are not further disadvantaged by being pushed further into the margins, losing their current source of income and being left worse-off as a result. This will require close working with the affected communities. A possibility is the development of a certification system that could be funded by product manufacturers to ensure that their supply chain meets high ethical standards.

It was noted that data on occupational hazards are of limited availability in some countries. This is true even for mining, an occupation for which the health risks have been recognised for decades. Data on the risks of artisanal mining and low-level secondary materials recovery are particularly lacking, despite the fact that the workers involved in these activities are at the highest risks. This applies even when activities, such as shipbreaking, are carried out on a major scale. Better data would facilitate dissemination of best practice in a more targeted manner than is currently possible.

6. Are adequate compensation systems in place for individuals and communities who suffer the consequences of poor health and a damaged environment?

7. How can best practice for protection of workers, local communities and the environment be more effectively disseminated? Safe working and good environmental performance is as routine in some regions as the lack of it is elsewhere. It is noted that poor practice is not confined to companies operating in their own countries but includes also external investors that do not operate as they would be required to in their domestic market.

8. Finally, are the social and economic consequences of business-as-usual understood? Put simply, the longer that contamination continues, the more difficult and costly it will be to clear up.

4.6. The roles of government and industry

Proposed roles for government are as follows:

- Recognise that the extraction and processing of metals, both primary and secondary, can impose significant burdens on society. Also, recognise that these burdens can be mitigated to a great extent through the use of established techniques for worker safety, pollution prevention, etc.

- Recognise that many companies already operate to high standards in the competitive global marketplace. This demonstrates the affordability of actions to protect workers and the local environment.

- Enforce good governance of mining and metals processing activities to ensure that hazards are rigorously controlled.

- Promote best practice in the metals industry, utilising information already available from sources such as the BAT (Best Available Techniques) Reference Notes produced by the European Commission's Joint Research Centre.

- Develop a circular economy strategy that includes systems for improved waste management. Recognise that delaying this action will generate substantial costs of environmental remediation in the near future in addition to the harm being caused at present.

For the metals industries the following are recommended:

- Adoption of best practice to minimise exposure of workers to hazardous substances and risks of accidents.

- Adoption of best practice to minimise environmental contamination and other risks (such as traffic burdens) imposed on local communities by major industries.

- Collaborative working between companies to maximise the quantity of metal gained per unit of ore extracted.

- Investment in R&D for the recycling of novel materials and new applications of materials.

- Collaboration with government to establish efficient systems for the collection of recyclable materials.

- Collaboration with manufacturing industry to ensure the traceability of supplied metals.

For manufacturing industry, four specific roles are envisaged:

- Ensuring that materials are ethically sourced, without exploitation of either workers (including children) or those who live close to sites that mine or process metals. This would require certification, which in turn could assist governments in the generation of data to better understand the hazards and risks faced by workers.

- Manufacturing goods that can be disassembled easily to facilitate recycling generally, but specifically to assist the recovery of materials for which supplies are limited.

- Investment in R&D to substitute away from the use of hazardous materials, and minimising their use when substitution is not feasible.

- Investment in R&D to increase the efficiency of metals use in products.

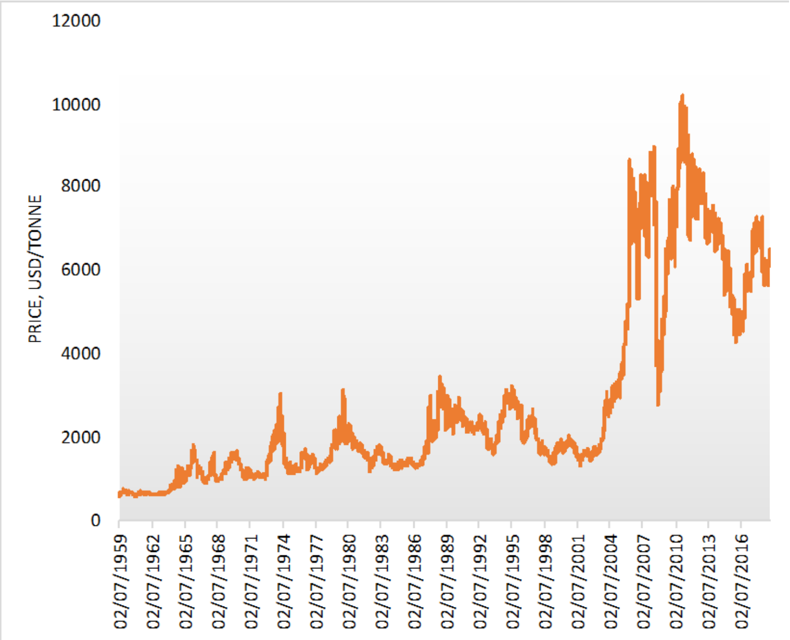
Annex A. Copper

Production and reserves

The US Geological Survey estimates global reserves of economically extractable copper are around 800 million tonnes, with the major producers being Chile, Peru, China and the USA (USGS, 2018a). Current production is around 19 million tonnes annually, the largest share (27%) coming from Chile. Resources amount to several billion tonnes, though this includes copper that is at concentrations considered too low for commercial extraction, or in locations that are currently too difficult to access. Copper is the third most recycled metal (by weight), after iron and aluminium.

Variation in copper price since 1960 is shown in Figure 3-1. The effect of changes in the global economy is clear, particularly in relation to the 2008 recession. Over the last decade, prices have varied between USD3,000 and USD10,000, which will affect the attractiveness of exploring new resources for both virgin and recycled metal.

Figure 3-1. Copper price trends, 1960-2019

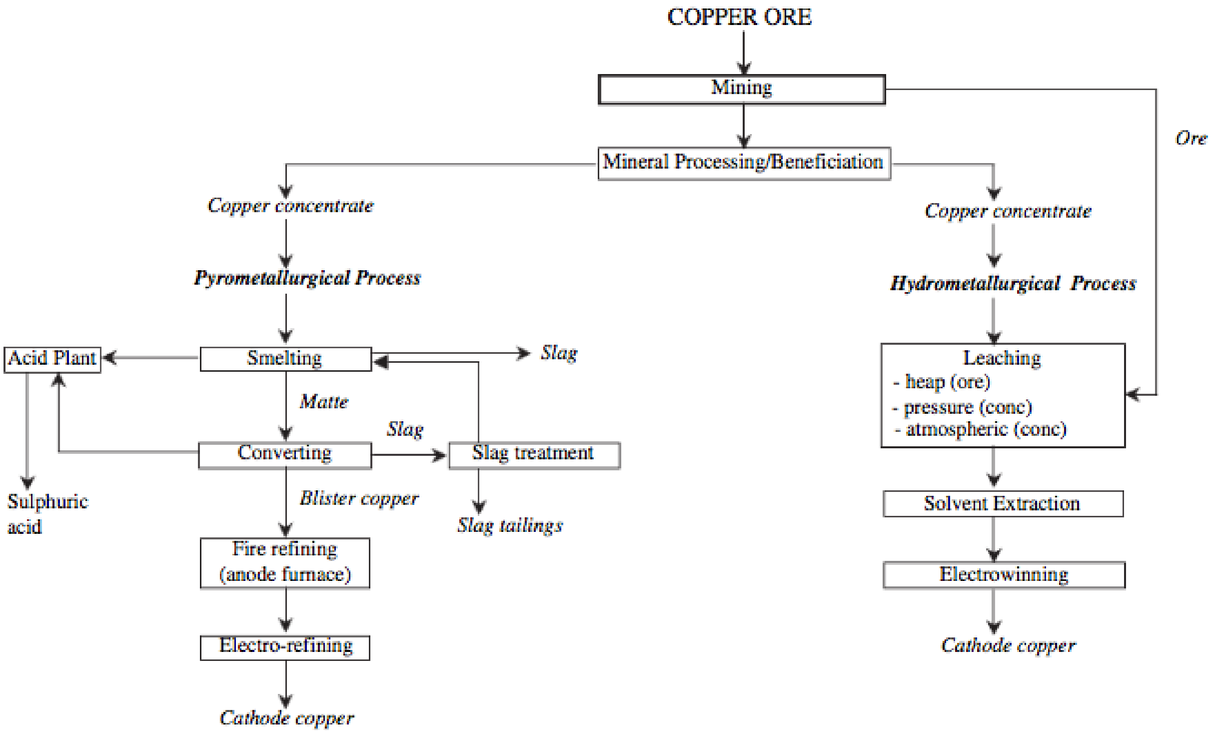


Source: https://www.macrotrends.net/1476/copper-prices-historical-chart-data

Copper production processes

Processes for copper production are shown in Figure 3-2. The most common approach is the pyrometallurgical route used for sulphide ores, with the hydrometallurgical process for oxide ores representing only an estimated 10% of global throughput (Calvo et al., 2016). In the pyrometallurgical process, the ore is mined, concentrated, smelted and refined. The sulphides are separated using flotation to form a concentrate containing 25% to 35% of copper, often at or close to the mine site to minimise transportation requirements. This is then fed to a smelter, along with oxygen and a reductant, such as coking coal, where sulphides are oxidised, producing a blister (unrefined porous copper containing small blisters from dissolved gases) of 97%–99% of molten metallic copper that is later purified by electrolytic purification to pure (>99.9%) copper. In the hydrometallurgical process, the copper is dissolved to produce a copper sulphate solution, after which it is recovered through solvent extraction and electrowinning to produce pure (99.99%) copper cathode.

Figure 3-2. Main processing routes for primary copper production

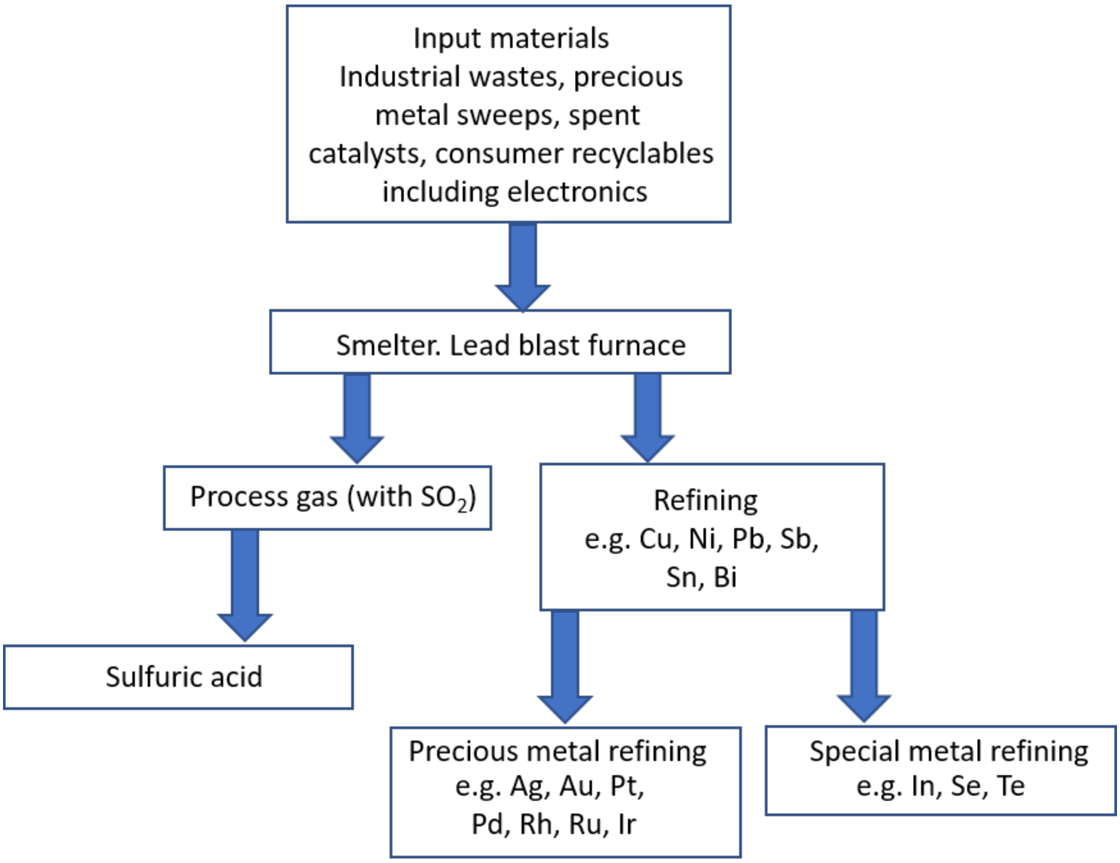


Source: Norgate et al, 2006

Recycling processes vary in complexity, depending on the quality and type of material accepted for reprocessing. Some facilities are very simple, using scraps that require only limited treatment and refining. Relatively pure scraps may be fed into primary production processes at the refining stage, when the copper is already relatively pure. To illustrate the other extreme, Hagelüken (2006) provides a process diagram for the recycling of much more complex electronic scrap at a highly integrated plant in Belgium (a simplified version of which is provided in Figure 3-3). The Figure illustrates the highly integrated nature of the process, with many metals and sulphuric acid being recovered through the process. Advanced plant are capable of handling a variety of feed materials including industrial wastes and by-products from other non-ferrous industries, precious metals sweeps, spent industrial catalysts and consumer recyclables, such as car exhaust catalysts and printed circuit boards/electronic components.

The metals recovered at the Belgian plant described by Hagelüken (2006) include gold, silver, palladium, platinum, rhodium, iridium, ruthenium, selenium, tellurium, indium, antimony, tin, arsenic, bismuth, lead and nickel as well as copper. Other by-products of the plant are sulphuric acid and a depleted slag, which is used as construction material and in the concrete industry.

Figure 3-3. Simplified flowsheet for an advanced integrated metals smelter and refinery



Occupational health risks of copper mining and production of copper concentrate

This section deals with occupational health linked to both copper mining and production of copper concentrate, given that the two activities tend to take place at the same site. In general, data on the effects of mining on occupational health tend to be most complete for accidents involving death or injury, and far less complete for occupational disease. Contributing factors for this pattern are the time taken for disease to develop and variation in the reporting requirements between countries.

The literature review carried out here has found limited data on the occupational health impacts of copper mining specifically. Data tend to be aggregated for mining activities generally, with sector specific information rarely available, and not specific to individual metals. For copper, the most extensive information on accidents is available for Zambia, the 7th largest producer in the world, and much of this section and the next is focused on that country. Rates for occupational health impacts reported here should not be seen as globally representative of the industry, but they do demonstrate the types of effect that occur, and also provide data on the potential for improvement.

Michelo et al. (2009) provided analysis of occupational injuries and fatalities in one of the largest copper mining companies in Zambia. The company employed 15 000 workers at 4 sites. Between January 2005 and May 2007, 165 injuries involving the loss of at least one working day and requiring medical treatment and 20 fatalities were recorded.

Table 3.1. Accident data for a Zambian copper mining company

January 2005 to May 2007

	Workers	Injuries [a]	Injury frequency (annual) [b]	Fatalities	Fatality frequency (annual) [b]
Underground	6 338	85	555	17	111
Engineering	826	10	501	0	0
Processing	3 617	46	526	1	11 [c]
Open pit / construction	2 601	20	318	1	16 [c]
Corporate	542	4	305	1	76 [c]
Total	13 294	165	514	20	59

Notes: a) Injuries included are those where medical attention was needed and reported and workers had at least 1 day off work. b) Injury and fatality frequencies are both calculated per 100 000 workers per year. c) The original source does not provide frequency numbers for these cases given the low number of fatalities over the period (1 in each case).
Source: adapted from Michelo et al., 2009.

The highest frequency rates of fatalities and injuries were seen amongst underground workers and the most common cause of fatal injuries was rock fall in the underground mines (of the 20 miners who died in the period examined, 17 worked underground). The most frequent mechanism of injury was handling of tools and materials, and the most commonly injured body parts were the hands and fingers which can of course have a major impact on ability to work. Michelo et al. concluded that Zambian rates for occupational accidents were higher than for metals mining in other countries. However, since 2007, it appears that there have been significant improvements in mining safety in Zambia. The Zambian Business Times (27/11/2017) reported that there were 13 deaths in the country's mining industry in 2016 (noting that the data in Table 3.1 are for a single company, operating 4 mines). However, by November 2017, only 1 fatality had been reported in the industry, the death of a truck driver involved in a crash with another vehicle. It is not possible here to make a thorough evaluation of the extent to which such interventions resolve the problems of the metals mining industry in the country: however, it is apparent that action has been taken on a number of prominent issues.

It is understood that there is little artisanal mining (a sector for which accident rates are often high and under-reported or not reported at all) of copper in Zambia, with such activity focused more on gemstones (Kambani, 2001). The same is not true of all countries where copper is produced: in a report focused on cobalt mining in DR Congo, Amnesty International and Afrewatch (2016) identify some artisanal copper mining also. Siwale and Siwale (2017) identify negative consequences of the Zambian government's policy framework being skewed in favour of large-scale copper mining which they consider have worsened the outcomes of artisanal and small-scale mine operators in Zambia's emerald sector by displacing operators to areas with low economic viability. Siwale and Siwale argue for strengthening of institutional capacities to better disseminate best practice in the mining industry generally.

Limited information has been found on occupational disease related to copper mining. Chen et al. (1993) report increased rates of lung cancer in copper miners. Vergara (2005) describes evidence for silicosis amongst workers in the Chilean copper industry over the period 1930-1960. Skoczyńska et al. (2016) provides evidence for variation in lung function according to the activities undertaken in a Polish copper mine, with welders being particularly affected. Taken together, data indicate that various dusts and gases present in the air in underground copper mines are hazardous to workers health. As in coal mining, it is likely that effects on surface miners will be lower, given lower exposures.

With respect to effects on the local population, Herrera et al. (2016) concluded that stricter emission controls on copper and gold mining were needed in Chile given heightened risk of asthma and rhinoconjunctivitis in children living close to mines.

Quantification of risks to workers and the local population to gain an overview of related impacts is not possible given the limited data available. However, this review demonstrates that risks are present. They can be reduced with effective regulation and increased levels of mechanisation and automation at mining sites. These may have a number of benefits, for example increasing efficiency whilst reducing pollutant emissions, and improving safety. OECD (undated) provides an example where the use of driverless technology at an Australian iron-ore mine. Cosbey et al. (2016) found that this technology had the potential to reduce fuel consumption in mining operations by 10% to 15%, making a significant contribution to the profitability of the mining operation given that up to 30% of the total mine operating costs came from diesel usage (Bellamy and Pravica, 2011). whilst reducing maintenance costs by up to 8%. The productivity gains, cost savings and environmental benefits of increased automation can be off-set to a degree at least by impacts on employment and to local communities.

Environmental risks of copper mining and production of copper concentrate

Calvo et al. (2016) consider the link between ore grade and energy intensity for copper mining, concluding that the average ore grade has decreased by approximately 25% in the last ten years continuing a long-term trend. Over the same period, the total energy consumption at copper mines has increased by 46% whilst production has gone up by a smaller amount, 30%. Declining ore quality will also naturally lead to increased production of mine waste, as greater quantities of material are extracted per unit of copper produced.

Ore is processed to increase the concentration of copper prior to smelting. For the pyrometallurgical process the ore is crushed and ground to a size that enables a suitably high liberation of the copper sulphide and the unwanted "gangue" materials with low metal content. The ore is suspended in a slurry and reagents are added to make the sulphides hydrophobic. Air is passed through the slurry, with the copper containing fraction being brought to the surface where they form a froth that can be skimmed off. Further processing then removes excess silicates and some other sulphide minerals. At the end of the process a copper concentrate with between 25 and 35% copper is produced. For copper oxide ores, the process is different, with copper being leached using sulphuric acid. The resulting copper sulphate solution is then stripped of copper via a solvent extraction and electrowinning (SX-EW) plant and the acid returned to the process. These processes generate a number of environmental burdens. As in other parts of the production process, there are examples of good and bad practice. In a well-regulated environment, impacts should be very low. In environments where regulation is lacking or not enforced, substantial contamination of land and waters can occur.

Environmental contamination from copper mines can be extensive as demonstrated by the following examples illustrating problems from both routine releases of contaminants over the course of production, and accidental releases:

- The Marcopper mining disaster of 1996 in the Philippines, involved the failure of a drainage tunnel, leading to the release of 1.6 million m^3 into the local river system. A national disaster was declared by the government, after villages were inundated with sludge. Coastal fisheries collapsed after coral reefs were smothered with wastes. [11]

- The copper mine at La Oroya in Peru, operating since the 1920s, is linked to significant contamination with arsenic, cadmium and lead. Remediation works have been carried out, but their success is unknown. [11]

- In 2014, sulphuric acid from the Buenavista copper mine in Mexico impacted a 40 mile stretch of the Sonora River and contaminated the drinking water supply for 20,000 people. Agricultural production was significantly affected. [11]

- In 2015, mine operators were sued by local residents with respect to contamination of drinking water supplies and of agricultural land around the Konkola mine in Zambia.[12] An estimated 93 000 tonnes of industrial waste are generated in the area annually, with the mine regarded as the major polluter. Release of sulphuric acid is highlighted as a particular problem. Kayika et al. (2017) highlighted health risks linked to the consumption of fruit grown on mine tailings around the mine, given high copper and cadmium concentrations.

Nautilus Minerals highlights several of these cases in information promoting its own operations for undersea extraction of minerals, with ore being exported to China for concentration and further processing. Unusually, under their proposals, the site of copper concentration would be far removed from the extraction site. This would also create large volumes of waste, though the company claims that there are local

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[11] Appendix E: Additional copper mine case studies. http://nus.live.irmau.com/IRM/Company/ShowPage.aspx?CategoryId=438&CPID=1586&EID=37434714&masterpage=31.

[12] https://old.danwatch.dk/undersogelseskapitel/impacts-of-copper-mining-on-people-and-nature/

industries (steelworks, cement works, underground mines) that can use the tailings and leach residues generated during processing, though there seems to be no independent verification of this.

It must be stressed that it is possible to manage the environmental burdens of mining and production of copper concentrate. An Environmental Impact Assessment (EIA) for the Lumwana mine in Zambia (ECVL, 2005) identifies a series of negative impacts relating to physical disturbance of the land, environmental contamination from routine and accidental releases, inadequate waste management and sewage treatment and disposal and noise. ECVL states that "*These potential environmental impacts with the exception of permanent changes to the physical landscape resulting from open pit excavation, tailings storage facility, water dam, river diversion and waste rock dump construction can be prevented or successfully mitigated against by implementation of a sound environmental management plan*." The company then provides details of how it intends to manage the risks.

There is evidence, however, that management and pollution control systems do not always work. Release of acid from the Mopani mine in Zambia into the local water network following failure of a pump in 2008, is said to have affected over 1 000 residents with abdominal pains, diarrhoea and vomiting[12]. There is also the question of when controls are fitted: problems of SO_2 emissions from the Mopani mine in Zambia persisted for over 70 years, before an improved sulphur recovery unit (increasing rates from 50% to 97%) was installed in 2014 [13].

A further case in Zambia from 2017 is illustrative of regulatory systems being able to intervene in case of accidental release.[14] Acid spilled from a tanker following an accident entered the nearby river, killing fish. The acidity was neutralised, and the Zambia Environmental Management Agency and local residents were informed. Of course, whilst systems appear to have worked to resolve contamination after the accident, questions remain as to how the accident happened and the design of the tanker, in allowing strong acid to be released.

Health risks from collecting and initial processing of copper waste

Copper for secondary production comes from a variety of sources, end-of-life consumer waste including building materials, manufacturing wastes and by-products of primary metal production that contain sufficient copper to make recovery economically viable. Given that these materials are present in society before recovery commences there is little or no added risk from much of the basic handling operations that will be necessary for recycling, moving material from one location to another. There are, however, cases where the collection of materials for secondary production can affect risk more significantly as the following examples indicate.

1. Emissions arising from the shipment of secondary materials through the international trade in scrap. Associated effects seem likely to be small relative to

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[13] https://www.thisismoney.co.uk/money/markets/article-2546329/Death-Zambian-politician-stirs-Glencore-tensions.html, https://www.theguardian.com/business/2016/sep/18/glencore-court-ruling-in-zambia-may-trigger-new-pollution-claims.

[14] http://www.zema.org.zm/index.php/sulphuric-acid-spillage-kifubwa-river-solwezi/

the benefits of overall system efficiency once refining emissions are accounted for.

2. Consolidation of hazardous materials present in the waste stream. As already noted, copper is present with many other metals either naturally or in products (e.g. electronics). Placing secondary materials into the waste stream and enabling the separation of useful material from unwanted hazardous materials enables the latter to be concentrated into a much smaller volume, substantially reducing handling burdens and demand for space in specialised landfills that are designed to accommodate hazardous substances.

3. "Informal" processing of electronic waste (e-waste), where material is exported to countries lacking adequate infrastructure for safe dismantling of waste goods. Eurometaux notes that two thirds of e-waste from the European Union is not properly recycled, with too much being incinerated, landfilled or exported without guarantee of quality treatment.[15] Given the illegal and informal nature of these activities, there is little detailed quantitative assessment available; most available data are anecdotal. Particular concerns arise through exposure to fumes generated by burning insulation from copper wire (UNEP, 2004). Leung et al. (2007) found widespread contamination with metals at various sites in Guiyu, China, a village that has been "intensely involved" in e-waste processing. They concluded that copper and lead levels are sufficiently high in the area to pose serious health risks to workers and local residents. Lau et al. (2013) measured elevated exposures of workers to various metals, including cadmium, copper, chromium, lead, nickel and zinc. The international obligations on shipment of hazardous waste shipments are designed to prevent such problems but are still not rigorously observed.

In each case, as it is typical of activities that are subjected to limited regulation, there is a lack of data on the change in burden and hence associated health impacts (or in the case of paragraph 2, benefits) cannot be calculated.

Emissions from copper smelting and refining

Energy use in copper refining generates a significant burden on public health via emissions to air, especially of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and fine particles (PM). There are further direct burdens on health from the release of toxic metals and other trace pollutants, and indirect burdens from significant greenhouse gas releases. To illustrate the range of pollutants release, data taken from the European Pollutant Release and Transfer Register (E-PRTR) are shown in Table 3.2 for two sites, Huta Miedzi Głogów in Poland and the Aurubis plant at Lünen in Germany (the world's largest copper recycling plant). Both facilities are required to operate to the standards required of the EU's Industrial Emissions Directive. They were selected here simply because they provide the most extensive reporting of emissions of copper producers on the E-PRTR.

For Głogów, data are presented for both air and wastewater emissions sent off-site

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[15] https://www.eurometaux.eu/eu-policy/resource-efficiency/circular-economy/

for treatment. The site produced 465 kt of copper in 2016[16].

For Aurubis, only air emissions are reported, as wastewaters are treated on-site and subsequent releases to the environment are not expected to exceed the reporting threshold of the E-PRTR. The site produced 180 kt of copper in 2016[17]. There is additional recovery of secondary materials, such as other metals that are present in the feedstock for copper production (including lead and precious metals), occurring either on-site or at other locations. Sulphuric acid is also recovered. These activities directly reduce the environmental burdens via solid and liquid wastes generated by copper refining and indirectly reduce the burdens of industry more generally, by displacing production of the secondary products from virgin materials.

Table 3.2. Emissions to air and wastewater for copper production at sites in Poland and Germany in 2016 normalised to copper output.

	Głogów		Aurubis
	To air (kg/kt Cu)	To wastewater (kg/kt Cu)	To air (kg/kt Cu)
As	0.85	606	0.21
Cd	0.041	0.32	0.12
Cr		0.19	
Cu	5.1	29	7.8
Hg	1.4	0.62	0.39
Ni	0.11	9.8	0.53
Pb	4.6	40	5.7
Zn	1.8	64	29
Benzene	9.1		
PM_{10}	147		<278
NO_x	2 022		192
SO_2	5 957		4 867
CO_2	2 064 516		961 111
CO	4 344		
Cl		9 333	
Cyanides		0.71	
F		1 077	

Source: Adapted from data from the European Pollutant Release and Transfer Register, https://prtr.eea.europa.eu/#/home.
Note: The sites are Huta Miedzi Głogów in Poland and the Aurubis site at Lünen in 2016. No PM_{10} emission is cited for Aurubis, indicating total emissions are below the reporting threshold of 50,000 kg per year.

Both sites produce other metals and materials in varying quantities, which are not accounted for in the normalisation of emissions which is only performed against copper output. Emissions of SO_2 per unit of copper production capacity are similar for the two plant, but emissions of NO_x and CO_2 are significantly lower (by factors of 10 and 2 respectively) for Aurubis. Emissions of metals show a more mixed picture, with the recycler having the lower emissions for most, but not all, presumably reflecting difference in the feedstock.

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[16] https://kghm.com/en/our-business/metallurgy-and-rafinery/glogow

[17] https://www.aurubis.com/binaries/content/assets/aurubis-en/dateien/financial-reports/2015-16/161213_geschaeftsbericht-gb-2016-en_final.pdf

Life-cycle emissions to air and associated health impacts

A number of studies provide life cycle analysis of copper production. For example, the European Copper Institute has provided LCA data for three products, roofing sheet, tubing and wire[18], whilst Hong et al. (2017) provide LCA data for production of copper from both primary and secondary sources. There is a focus here on work by Grimes et al. (2008) as it provides an international comparison of performance.

Variation in emissions between countries reflects a number of variables, including the quantity of copper produced, the design and efficiency of plant, the nature of feedstock materials (e.g. purity of scrap and other secondary materials), characteristics of the national energy sector with respect to fuels used, and emission controls in place.

Grimes et al. (2008) provide carbon foot-printing data for production of copper cathode from primary and secondary sources amongst the major global producers (Table 3.3). The benchmark value at the top of the table was developed by the authors to reflect what should be generally achievable by the primary and secondary industries. There is substantial variation between countries, largely reflecting differences in the energy sector. For example, Kazakhstan at the top of the list is heavily dependent on fossil fuel use, whilst Zambia, at the bottom, uses hydro for most of its electricity generation. For comparison with other sources, the right-hand column of the table includes results from Bosch and Kuenen (2009), though these are not split by primary and secondary production. Results indicate a similar order of magnitude to Grimes et al. though there are some significant differences (e.g. for Brazil) that underline the variability in results associated with the use of alternative assumptions on input parameters.

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[18] https://copperalliance.eu/benefits-of-copper/circular-economy/life-cycle-assessment/

Table 3.3. Variation in carbon intensity of the energy sector and carbon footprint of copper cathode from primary and secondary materials in different countries.

		kt CO_2/100kt Cu		
	Kg CO_2/GJ_{el}	Primary producers	Secondary producers	Estimates by Bosch and Kuenen (2009)
Benchmark		**125**	**44**	
Kazakhstan	359	607		
India	277		175	
Australia	257	434	162	
South Africa	253		159	
China	233	394	147	272
Poland	203	343	128	312
Indonesia	201	339	126	
US	188	317	118	191
Iran	166		105	
Mexico	165	279	104	178
Germany	150		94	205
UK	132		83	
Japan	116		73	220
Russia	98	165	61	
Venezuela	70		44	
Chile	92	156		
Canada	62	105	39	99
Peru	41	70		
Brazil	26		16	136
Zambia	1.9	3		

Source: Grimes et al. (2008), adapted from Bosch and Kuenen (2009).

UNEP (2013) provides emissions data for PM10, SO2 and arsenic (Table 3.4) for four copper projects in Australia and Chile, covering all stages of production. Figures normalised per unit of copper production vary significantly, reflecting again variability in the fuels used through the life-cycle, emission controls in place, etc. The table demonstrates the potential for significant improvements in performance comparing particularly Project 3 with the others.

Table 3.4. Pollutant emissions from copper projects in Australia and Chile covering the four stages of primary copper production (mining, milling, smelting and refining).

	Cu	SO_2	PM_{10}	As
		Tonnes per year		
Project 1	893 952	101 199	524	498
Project 2	386 639	184 904	1 263	332
Project 3	175 216	1 988	976	0.52
Project 4	71 967	84 453	1 234	498
		kg per tonne of copper		
Project 1		113	0.59	0.56
Project 2		478	3.3	0.86
Project 3		11	5.6	0.003
Project 4		1 173	17	6.9

Source: UNEP, 2013

Damage cost assessment for health impacts of air pollutants

Health impacts and economic costs can be calculated from knowledge of:

- Emissions (as in Table 3.5)

- Damage costs per unit of pollution.
- The location of plant

Given the broad spread of results for emissions shown in Table 3.4, it is necessary to construct scenarios to illustrate the potential differences in performance. Analysis is focused on exposure to SO_2, NO_x and PM_{10}, and CO_2 releases are also considered. Data are provided in Table 3.5 with information on the derivation of the estimates provided below the table. It is acknowledged that there are significant uncertainties in these calculations and as such they should be seen as providing guidance on the broad order of magnitude of likely impacts under alternative conditions, rather than anything more precise. The largest uncertainties concern sulphur emissions, as these arise in significant quantity from two possible sources: power generation and production of copper concentrate at or close to mines. The LCA data in Table 3.4 indicate variation over two orders of magnitude for SO_2.

Table 3.5. Variation in emissions from primary and secondary production of copper.

Units: tonnes of pollutant per tonne of copper.

	Primary production			Secondary production		
	Low	Mid	High	Low	Mid	High
SO_2	0.013	0.46	1.22	0.0048	0.05	0.20
NO_x	0.018	0.087	0.156	0.0067	0.032	0.058
PM_{10}	0.00062	0.0059	0.0165	0.00023	0.0021	0.0061
CO_{2e}	1.25	1.54	6.07	0.44	0.57	2.24

Notes: For emissions from primary production: SO_2 from Table 3.4. NO_x calculated using the ratios of NO_x:SO_2 from Table 3.2, combined with the SO_2 data here. PM_{10} from Table 3.4. CO_2 low uses benchmark from Grimes et al. (2008), mid and high from Table 3.3. NO_x, PM_{10}, CO_{2e} from secondary production: Calculated as [primary production emission]*0.37, reflecting the ratio used by Grimes et al. (2008) for quantification of CO_2 emissions for secondary.

For secondary production, it is considered here appropriate to exclude the release of SO_2 at mine sites from copper concentration. For secondary materials composed of copper that has already been refined, this is not relevant: the recycling process does not affect the releases early in the life-cycle. The same is assumed for secondary materials generated from primary production, on the basis that the secondary materials are not assumed to be a major factor in deciding to produce copper from ore.

The main factors causing variation in the emissions data relate to:

- Regulatory controls on emissions at the mine/site of copper concentration
- Regulatory controls on emissions from the power sector
- The fuels used during the process and in the production of electricity

The location of plant is a significant factor in determination of the damage costs per unit of pollution. Facilities that are located in densely population regions naturally cause significantly higher health damage than those where population density is lower. Damage costs per tonne of pollutant are taken from EEA (2014), a study carried out by the European Environment Agency to quantify the damage associated with emissions from the major industrial facilities of Europe. There is roughly a factor

10 difference in damage costs for each pollutant across the ranges shown. Whilst the report provides data for all EU countries, attention here focuses on the results for Lithuania, as it has a population density (43 people per km^2) similar to the average of the main copper producers (45 people per km^2). The EEA damage cost data are based on use of the exposure response functions recommended by WHO-Europe through the HRAPIE (Health Response to Air Pollutants in Europe) study for the European Commission (WHO, 2013).

Table 3.6. Damage costs of the major air pollutants: Range for European countries, and data for Lithuania. Values updated to EURO, 2018.

	Damage (€) per tonne of pollutant		
	Europe low	Lithuania	Europe high
NO_x	3 700	11 800	40 200
PM_{10}	12 300	36 800	124 300
SO_2	14 200	35 500	88 400

Source: Adapted from EEA (2014)

Note: The calculations that follow are based on application of the estimates for Lithuania only. Other data are provided in the table to illustrate the potential range around the best estimates for specific sites.

Combining the data on emissions and damage costs to generate possible ranges for damage could give an overall range that is so broad (roughly a factor 60 from extreme low to extreme high) as to be uninformative. The analysis is therefore structured around the following scenarios:

- **Scenario 1:** Low emissions, corresponding to high levels of environmental regulation and high contribution of renewable energy to the electricity mix

- **Scenario 2:** High emissions, corresponding to low levels of environmental regulation and high contribution of fossil energy to the electricity mix

Results are shown in Table 3.7, for Scenario 1 (low emissions) and in Table 3.8 for Scenario 2 (high emissions), in both cases taking the mid estimates of damage per tonne corresponding to the average population density observed in the main copper producing countries. It is clear that results are dominated by SO_2 emissions. From the assumptions used in the analysis, the impacts of secondary production are naturally significantly lower than from primary production.

Table 3.7. Estimates of the costs of air pollution associated with production of 1 tonne of copper by primary and secondary routes for Scenario 1 (low emissions).

	Primary production		Secondary production	
	EUR	% of total	EUR	EUR million
SO_2	461	63%	143	54%
NOx	213	29%	66	25%
PM_{10}	6	1%	7	3%
Subtotal	**674**		**209**	
CO_2	50	7%	50	19%
Total	**731**		**266**	

Results for Scenario 1 indicates that primary production generates health impacts from air pollutant emissions that are a factor 2.8 higher than those linked to secondary production.

Table 3.8. Estimates of the costs of air pollution associated with production of 1 tonne of copper by primary and secondary routes for Scenario 2 (high emissions).

	Primary production		Secondary production	
	EUR	% of total	EUR	EUR million
SO_2	43 307	95%	7 099	88%
NOx	1846	4%	686	9%
PM_{10}	607	1%	225	3%
Subtotal	**45 153**		**7 786**	
CO_2	50	0%	50	1%
Total	**45 810**		**8 060**	

Results for Scenario 2 indicates that primary production generates health impacts from air pollutant emissions that are a factor 5.7 higher than those linked to secondary production. Application of the ranges for damage costs would give upper and lower bounds roughly a factor 3 lower and higher than the estimates shown. Damage costs are based on average European Union incomes. The difference between Scenarios 1 and 2 is largely explained by the variation in SO_2 emissions shown in Table 3.4 and Table 3.5. These emissions arise largely from ore processing and specifically from the copper concentration step, separating the copper from much of the unwanted material present in the ore.

Summary of the risks of copper production and health

The risks and burdens discussed above are summarised in Table 3.9.

Table 3.9. Summary of the burdens and impacts of primary and secondary copper production.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for 'artisanal' mining. Substantial reduction in risk through effective regulation and mechanisation.	Not applicable.
Initial processing, production of copper concentrate	Emissions of SO_2 to air, with potential for significant health damage. Emissions of acids, metals and other pollutants to water, contaminating land and drinking water. Spills of acid, again contaminating land and drinking water. Controllable via regulation.	High risk where informal processing is carried out, with particular concern over the dismantling and processing of e-waste, including the burning of insulation from wires. Emissions include lead and dioxins. This may affect workers, their families and neighbours. Substantially lower relative to primary production in well-regulated environments, given the reduction in SO_2 emissions.
Production of refined copper	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Discharge of metals and some organics to waters. Emissions can be closely controlled, both to air and water.	Similar types of impact to those from primary production of copper. However, the process is more efficient and leads (all else being equal) to reduced inputs, by around 60%.
Transport	Impacts will be dependent on transport distances. These are generally significant given the regions where copper is produced and major markets.	Generally low, given that secondary materials will need to be moved for disposal if not recovery. However, may become large through international trade in secondary materials.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, ore quality and fuels used, especially for power production. Quantified health impacts related to air pollutant emissions are estimated at EUR 730/t of copper under a low emission scenario driven by effective regulation of emissions and renewable energy use, and EUR 46,000/t of copper under a high emission scenario with limited emissions regulation and high fossil energy use. Impacts other than air pollutant effects are not included in these figures.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production. Quantified health impacts related to air pollutant emissions are estimated at EUR 260/t of copper under a low emission scenario driven by effective regulation of emissions and renewable energy use, and EUR 8,000/t of copper under a high emission scenario with limited emissions regulation and high fossil energy use. Impacts other than air pollutant effects are not included in these figures.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

Annex B. Rare earths

The Rare Earth Elements

The rare earth elements are listed in Table 4.1 together with information on their uses and abundance in the earth's crust. They are comprised of elements with atomic numbers from 57 to 71, and two lighter elements, scandium and yttrium, with similar properties. The table lists a variety of their uses, typically in technical applications. One of the rare earths with widespread application is neodymium, which is used to manufacture high-strength magnets used for example in the microphone and speakers of mobile phones and in much larger magnets used in wind turbines. Other uses include numerous applications in medicine, catalysts in oil refineries, components of electric vehicles and control rods for nuclear reactors. With the exception of promethium, the rare earth elements are not rare, with an overall abundance in the earth's crust similar to copper. However, they are more disperse than other mined metals, meaning that economically exploitable ore deposits are not common, and their recovery from ore is more difficult.

Table 4.10. List of the rare earths, with examples of application and abundance

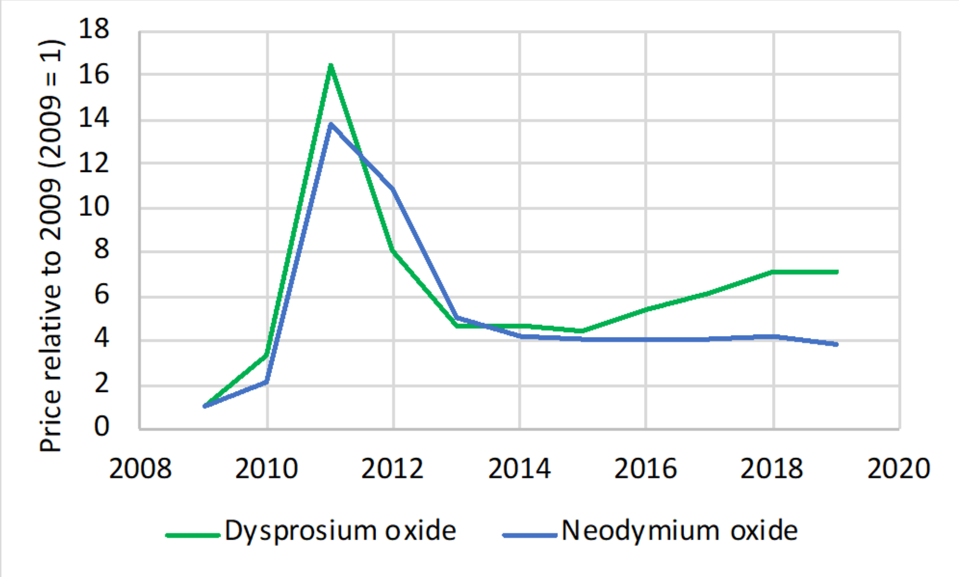
	Examples of uses	Abundance (ppm)
Scandium	Light alloys, radioactive tracers, additive for lamps	22
Yttrium	Lasers, lighting, superconductors, spark plugs, cancer treatments	33
Lanthanum	High refractive index glass, camera lenses, electrodes, hydrogen storage, catalysts	39
Cerium	Glass colourant, catalysts, oxidising agent	66.5
Praseodymium	Rare earth magnets. Lasers, ceramic colourant, motors for EVs	9.2
Neodymium	Rare earth magnets, lasers, motors for EVs, capacitors	41.5
Promethium	Nuclear batteries, luminous paint	1.10^{-15}
Samarium	Rare-earth magnets, lasers, neutron capture, masers, control rods of nuclear reactors	7
Europium	Lasers, lamps, NMR relaxation agent	2
Gadolinium	Glass, lasers, computer memories, medical appliances, magneto-restrictive alloys	6
Terbium	Magnets, phosphors, lasers, lamps, fuel cells, magneto-restrictive alloys	1
Dysprosium	Rare earth magnets, lasers, hard disk drives	5
Holmium	Lasers, magnets, optical photo-spectrometry	1
Erbium	Lasers, vanadium steel, fibre optics	4
Thulium	X-rays, metal halide lamps, lasers	0.5
Ytterbim	Lasers, chemical reducing agent, stainless steel, medical appliances	3
Lutetium	Tomography, glass, phosphors, catalysts, lamps	0.8

Note: Abundance in parts per million refers to the concentration of each element in the earth's crust.

The Heavy Rare Earths (Europium and those listed below it in Table 4.1) and Light Rare Earths were ranked first and fourth respectively by Coulomb et al. (2015) in terms of critical raw materials subject to supply risk. Within these groups there will of course be variability in supply risk, with some elements having a higher risk than others. Supply risk will also change over time. It may be reduced, for example, by innovation around 'riskier' metals in terms of efficiency of use (attaining similar levels of performance whilst using less material) and substitution with substances that are more readily available. Alternatively, it may increase for some elements as novel applications are identified.

Prices of rare earths increased significantly in 2011 (Figure 4-1) largely as a result of decisions made by the Chinese government to control exports, against a background of increasing global demand and a lack of alternative sources (WTO, 2015). The reasons given for this action were related to conservation and protection of plant, animal and human safety. Outside of China, there existed a view that the measures were designed primarily to protect Chinese industry, though the country debates this and the matter was raised with the World Trade Organization. After 2011, prices soon fell back though stabilised at a higher level than before, where they have largely remained since. Around the same time, there were numerous announcements of recycling projects and interest in establishing new sources of primary production globally, though it is as yet unclear how successful many of these initiatives were. USGS (2018b) states that as of 2018, there remains little production of rare earths via recycling.

Figure 4-4. Price trends for dysprosium oxide and neodymium oxide, 2009-2019.



Source: www.statista.com.
Notes: Prices on the international market, yearly average, purity >99%.

Current production and reserves of rare earth elements

Data on mine output for 2016 and 2017 for rare earths are shown in Table 4.2. Production is still dominated by China, for which the industry has consolidated into six major industrial entities, alongside efforts to stem illegal production that was responsible for significant contamination of land (though contamination was generated by both legal and illegal operations). This reflects the situation discussed above for copper, where production standards, regulation and enforcement are extremely variable, leading to significant differences in the environmental burdens of operations between locations.

The leading supplier of rare earths outside China is Malaysia, mainly through the processing of mineral concentrates mined in Australia. As noted above, USGS (2018b) notes little production via recycling.

Significant quantities of REEs are estimated to be in use or available in waste products, especially e-waste. It was estimated[19] in 2010 that Japan had 300 000 tonnes of REEs and 6 800 tonnes of gold in e-waste, whilst Du and Graedel (2011) estimated that 485 000 tonnes of REEs were in use globally in 2007, 85% of which were cerium, lanthanum, neodymium and yttrium. Recycling of each of these was possible, but difficult. Recycling of other REEs would be difficult primarily due to technical challenges associated with separating the rare earths from the product. UNEP's metal wheel (UNEP, 2011, p.30) indicates that the rare earths and rare earth oxides are largely unrecycled for either technical or economic reasons. Relevant factors include:

- The high cost of dismantling electronics and separating out the components of electronics to distinguish parts with high levels of specific rare earths.
- The low concentration of the rare earths in many applications.
- The affinity of the rare earths for the dominant metals in products.

Table 4.11. World mine production and reserves of rare earths (tonnes)

	Mine production 2016	Mine production 2017	Reserves
Australia	15,000	20,000	3,400,000
Brazil	2,200	2,000	22,000,000
Canada	0	0	830,000
China	105,000	105,000	44,000,000
Greenland	0	0	1,500,000
India	1,500	1,500	6,900,000
Malawi	0	0	140,000
Malaysia	300	300	30,000
Russia	2,800	3,000	18,000,000
South Africa	0	0	860,000
Thailand	1,600	1,600	Not available
USA	0	0	1,400,000
Vietnam	220	100	22,000,000
World total	129,000	130,000	120,000,000

Source: USGS, 2018b.

Processes for the production of refined rare earth metals

The rare earths share a number of properties, leading them to be found together in geologic deposits, especially in bastnäsite, monazite and loparite ores and lateritic

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[19] https://www.nytimes.com/2010/10/05/business/global/05recycle.html

ion-absorption clays. The fact that they share similar properties also makes them difficult to separate and refine to acceptable standards.

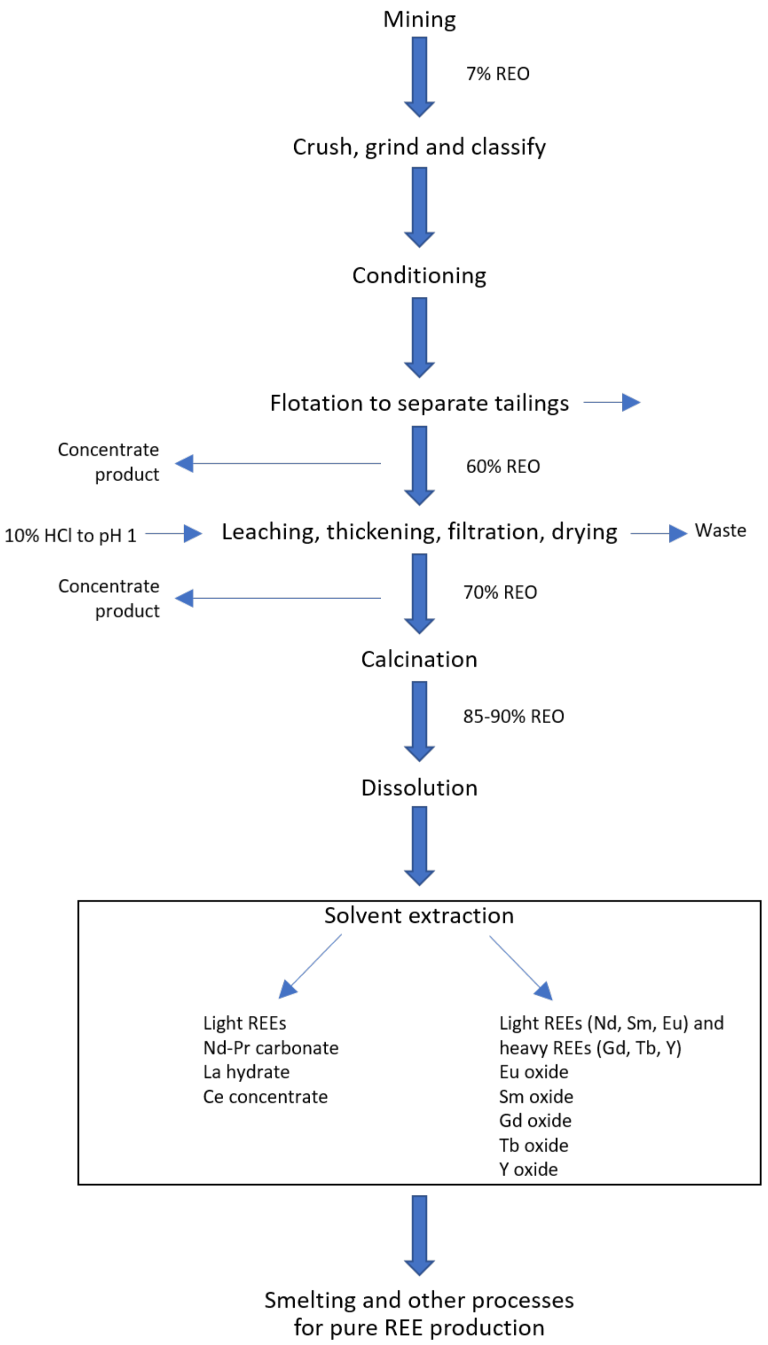
US EPA (2011) provides a review of production, processing, recycling and associated environmental issues. The report was written in recognition of the growing importance of REEs against a background where there had been no US production for a number of years, and the action by the Chinese government to control exports. The report provides a guide to the regulations that would affect new operations, from exploration through to mine closure.

The following process flow diagram has been adapted from materials presented in US EPA (2011) (Figure 4-2). There are similarities with copper production, for example through grinding and flotation, but also marked differences, particularly the solvent extraction processes in the final stages of separation. Following separation, electrowinning and electrorefining are used to produce pure metal.

Separation techniques developed in the 1950s and 1960s included ion exchange, fractional crystallisation and liquid-liquid extraction. Recent increases in demand for rare earths and concern over security of supply have led to research on novel extraction techniques, such as the use of bacteria to adsorb REEs onto their surface prior to release, with separation to the different elements possible by controlling the pH of a wash solution (Bonificio and Clarke, 2016).

For secondary rare earths, the final form of material will vary between recycling processes. For example, material may be recycled back to the elemental form, or to alloys: direct production of alloys during recycling seems an obvious route, given that the rare earths will often be re-used in the form of the same alloys that they started from. The difficulty here lies in the need to separate out specific components such as motors, microphones and speakers (all of which can be very small in common consumer goods) from articles deposited in the waste stream, rather than recycling a mixed batch of electronic and other waste by shredding and refining. The added processing costs may undermine the economic case for separation of the rare earths, leading to their eventual loss from the system. The difficulty of recycling rare earths can be contrasted with the relative ease of recovery of other metals that are used in relatively pure form, such as copper, lead and aluminium.

Figure 4-5. Simplified process flow diagram for rare earth production from bastnäsite ore



Source: Adapted from US EPA (2011)
Note: REO = rare earth oxide

Rare earth mining and processing of ores

This section considers all stages of production before smelting. As was the case for copper, there are examples of good and bad practice for extraction of the REEs. Concern focused primarily on unregulated production in China (given its near monopoly on REE production) in the 2000s and early 2010s. As already noted, the Chinese government has sought to formalise the market, consolidating production through 6 companies. This should reduce impacts on occupational and public health though no data have been found to confirm this.

Pollution during the mining process is mainly linked to following activities:

- Water usage and release of contaminated water during the extraction of the ores from rocks
- Release of acidity into the soil and surrounding environment, leading to contamination of food and environmental damage
- High energy use, reflecting the low abundance and varying spatial distribution of REEs
- Generation of dusts containing REEs and other substances.

US EPA notes that waste rock storage piles are typically large and can represent a significant source of toxic metals. Rainwater and other water draining the site should therefore be collected to ensure that it does not contaminate the surrounding land and waterways. Fugitive dusts containing metals common to the ore material are also a concern from waste rock storage piles.

US EPA (2011) identified four waste streams that would likely be classified hazardous:

- Waste solvent due to ignitability
- Spent lead filter cake due to toxicity
- Waste zinc contaminated with mercury due to toxicity
- Solvent extraction crud due to ignitability.

However, the major environmental risk in mining and processing rare earths is associated with the treatment and disposal of the tailings (Schüler et al., 2011). US EPA (2011) defines a worst-case scenario as dam failure, linked to poor construction or a catastrophic event, which can result in serious long-term damage.

US EPA and Öko-Institut highlight issues in China, noting that small illegal operations typically have no environmental controls, whereas larger operations only started using controls in the 2000s. The Bayan-Obo mine has an 11km^2 tailings impoundment that has radioactively contaminated the soil, groundwater, and vegetation of the surrounding area. As reported by Hurst (2010), The Chinese Society of Rare Earths stated that every tonne of rare earth metal produced generates approximately 8.5 kg of fluorine and 13 kg of dust. Also, they reported the use of concentrated sulphuric acid during high-temperature calcinations produces 9 600 to 12 000 m^3 of waste gas containing dust concentrate, hydrofluoric acid, and sulphur dioxide, and approximately 75 m^3 of acidic wastewater, as well as 1 tonne of radioactive waste residue. Additionally, the REE separation and refining process known as saponification has been estimated to have generated 20 000 to 25 000 tonnes of wastewater in 2005, containing high concentrations of ammonia (Öko-Institut, 2011).

US EPA (2011) also note historic contamination of groundwaters and soils at US REE sites. They note a number of actions to be taken at the Molycorp Mountain Pass site prior to its reopening, including measures to re-use waste waters improved processing to reduce waste and recycling of acids and bases used to extract the REEs.

Collecting rare earths for secondary production, and initial processing

Collection of rare earths for secondary production occurs at three stages. The first concerns manufacturing waste and the second end-of-life goods, including e-waste, motor vehicles and industrial items such as wind turbines. A third stream of materials concerns wastes from standard RE production processes. Efficient collection schemes are necessary to enable a significant level of recovery. Within the EU, these are stimulated under the Circular Economy Package through Extended Producer Responsibility schemes, where producers are responsible for goods through to the end of life phase, and separate collection of certain kinds of waste is mandatory. Legislation exists on specific product types through the Batteries Directive, the End-of-life Vehicles Directive and the Waste Electrical and Electronic Equipment (WEEE) Directive. There will inevitably be some increased demand on transport from such systems, though it is against a background where collection would be needed in any case. The collection of materials may facilitate export to other regions of the world for reprocessing, which would drive up transport burdens.

The rare earth processing plant at La Rochelle in France has focused much effort on processing of material normally discarded at the end of their refining process. The material contains significant levels of REEs, but at a concentration too low for standard processing. The process used by the site operator makes more complete use of extracted materials and has other important benefits, notably that the feedstock contains no radioactive thorium (Solvay, 2015). The site also recovers rare earths from Ni-Mh batteries and low energy lamps. A benefit of using these secondary material streams is that they do not contain radioactive thorium, unlike some of the major rare earth ores.

Even where efficient collection schemes are present, it is not certain that REEs will be recovered. Those taking the waste for reprocessing may focus on other materials (copper, lead, precious metals), given the technical complexity and cost of recovering the rare earths. For some of the major uses (e.g. in wind turbines and for car batteries) there may be a significant time (10-20 years) between the sale of goods and its emergence on the end-of-life materials market. This lag may provide relevant industries time to develop the capacity required for processing.

Initial processing of materials can have significant impact on the potential for recovery. Sprecher et al. (2014) found that shredding hard drives for recycling resulted in a 90% loss of neodymium, and instead proposed a method in which hard drives are taken apart by hand as a way to address this issue. Separation of electronics into their component parts will simplify subsequent recovery of rare earths but is of course time-consuming and resource-intensive and can expose workers to additional hazards through exposure to the materials present inside electronics and physical risk from dismantling equipment.

Purification processes

US EPA (2012) lists a number of processes for reducing the product of initial processing (e.g. RE oxides) from primary and secondary production to obtain pure metal. Smelting is the most widely used method, with reductants reacting in the furnace with oxidants (e.g., oxygen, sulfide, carbonate) to separate and free the metal. Less common processes include electrolysis, gaseous reduction, vacuum distillation and mercury amalgamate oxidation and reduction.

Hazards to health arise from the energy used in the process particularly through the release of air pollutants, and some of the waste materials that are generated. As in other cases, the potential for these to cause harm are dependent on the regulatory environment in place, on-site controls to prevent releases to the environment and exposure of workers, and the source of electricity.

Health impacts of the processing chain for production of refined rare earth metals

The health risk of exposure to the REEs varies between the different elements, some are known to be harmful, others are relatively harmless. Pagano et al. (2015) note that the literature is limited, focused mainly on cerium and lanthanum. Effects observed amongst workers include cancer, respiratory disease, dental loss and death. The lung and liver seem particularly sensitive. Zhuang (2017) express concern over possible neurological effects on children. Significant bioaccumulation or rare earths has been observed in populations living close to production sites, particularly the illegal sites that have been targeted by the Chinese government.

Production of rare earths involves the use of corrosive substances. These may affect health through direct exposure or through environmental contamination. Some of the waste products from mining are hazardous: notably, monazite was originally mined for its high content of radioactive thorium rather than for rare earths (Lima et al., 2018). Monazite also contains uranium in significant quantities. The presence of these elements has been a factor leading to the preferential exploitation of bastnäsite ores. Materials such as these are likely to be transferred to mine tailings or other waste dumps where they may lead to exposure of the population.

Production is also energy-intensive, leading to further harm from emissions from power generation, through exposure of workers and the population to burdens dependent on the source of electricity. It is reasonable to assume that coal is used for the electricity used for most REE production, given the dominance of coal in the Chinese power sector[20], and the dominance of China in REE production.

In each of these areas, examples of both good practice, where hazards are identified and properly managed, and bad practice, where they are little more than ignored, can be identified. There is further variation linked to the type of ore being mined, and the

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[20] https://chinaenergyportal.org/en/2017-electricity-energy-statistics/

dominant sources of power in mining regions.

With respect to secondary materials, hazards to the workforce arise during the dismantling of e-waste through accidental injury and exposure to hazardous substances, such as lead and other metals. Given the limited amount of REE recovery at the present time, however, such risks may not currently be significant.

There is also potential for uncontrolled release of REEs after they have been used. Badaram (2019) discusses the use of gadolinium (Gd) as a contrasting agent for magnetic resonance imaging (MRI) in medicine. Patients are dosed with chelated Gd (chelated to eliminate toxicity) to improve the quality of imaging. The Gd is passed from the body in urine, and is able to then pass through water treatment systems almost unaffected into the aquatic environment, leading to significant accumulations of the substance in some areas and transference to drinking water systems (Birka et al., 2016a, b). Hatje et al. (2016) report a considerable increase in REE concentrations, including Gd, in San Francisco Bay. This is a growing concern given the limited knowledge of the health impacts of these elements.

Life-cycle emissions to air and associated health impacts

A number of LCA studies have been carried out on rare earth production. In all cases, results are sensitive to assumptions made during the analysis, including the allocation of burdens to individual rare earths. This is, for example, performed by reference to market prices or the mass of product generated (Marx et al., 2018). Results will be sensitive to the method used for allocation, and changes in price over time, or differences in the relative share of different REs being produced.

This section starts with a 2014 review by Navarro and Zhao, and then proceeds to discuss other significant studies in largely chronological order. Navarro and Zhao found that LCA studies were dominated by assessments of the Mountain Pass mine in the USA and of the Bayan Obo mine in China. Data for Mountain Pass were, however, about 20 years old by the time of writing. Navarro and Zhao (2014) highlights issues relating to LCA tools, for example in relation to the mix of ores assumed, rare earth content of ores and pollutant control technologies in place. They also discuss issues of allocation of burdens between activities, noting that the Bayan Obo site produces iron ore as well as rare earths. They also note significant variation in estimates of burden between different authors, with, for example, the carbon footprint of neodymium varying from 12 kg CO_{2eq} to 66 kg CO_{2eq} per kg Nd. Such variation is in part due to variation in the systems used to extract the REEs, local sources of electricity, and variation in the methods and assumptions adopted in the LCA work.

Weng et al. (2016) reports significant knowledge gaps in LCA databases for different routes for producing REEs in different regions and from different minerals. They consider that despite their importance in the global economy, there has been minimal research assessing the environmental impacts of REE mining. They present a “cradle-to-gate” scale life-cycle impact assessment for 26 operating and potential REE mining projects, focusing on the gross energy requirement and the global warming impacts of the primary REE production stage. Key conclusions are:

- Declining ore grades significantly increase the environmental impact of REE production.

- On a unit basis (such as GJ/tonne-metal or kg CO_{2eq}/tonne-metal), REE production causes higher environmental impacts than common metals (e.g. Cu, bauxite and steel), with the refining stage being responsible for the greatest proportion of these impacts.

- Changing the REE production configuration could lead to diverse environmental footprints associated with each project.

Pell et al. (2017) provide a critique of the Weng et al. paper, and identify a number of problems with it, for example:

- Discussion by Weng et al. focuses on a subset of impacts.

- Some of the comparisons presented in the paper are not true like-for-like comparisons, dealing with varying parts of the full life-cycle.

- The functional unit is inconsistent.

These caveats need to be considered in any use of the results.

Zhou et al. (2016) focused on production at the Bayan Obo mine, which accounted at that time for about 50% of total Chinese production of rare earth oxides (and by extension, a substantial part of global production, given Chinese domination in the market). Life-cycle inventory results for air pollutants from mining and smelting activities linked to the production of 1 tonne of rare earth oxides are summarised in Table 4.3. The figures in the table indicate that most emissions to air are from smelting activities, with emissions linked to electricity use dominant. Inspection of other data presented indicates that the major source of electricity is coal (as would be expected in much of China).

Table 4.12. Life cycle inventory data for major air pollutants for production of 1 tonne of rare earth oxides at Bayan Obo.

	CO_2 (t)	SO_2 (t)	NO_x (t)
Mining	2.4	60	30
Smelting	37	860	420
Total	**39**	**920**	**450**
From electricity use	28	830	420
% from electricity use	70%	91%	93%

Source: Adapted from Zhou et al (2016)

These data indicate that the production of REEs is significantly more polluting per unit mass of end product than copper production (see Table 3.5).

Zhou et al. note that the largest pollutant streams linked to Bayan Obo are carbon dioxide and ammonia in the wastewater. The paper indicates that treatment of the wastewaters is being considered but has not been installed (it is stated that “ammonia nitrogen wastewater can be properly handled with new technology”). Zhou et al. also notes that some significant environmental burdens are not included in their assessment, notably radioactive thorium (at a concentration of 0.032% in ore) and airborne particles.

Browning et al. (2016) provide an LCA of rare earth production from monazite and allocate impacts to specific rare earths, demonstrating a factor 10 variation between elements with respect to:

- Greenhouse gas emissions: average 65 kg CO_2e/kg, range 21.3 (europium) to 198 kg CO_2e/kg (yttrium)
- Water consumption: average 11 170 kg/kg, range 3 803 (samarium and gadolinium) to 29 902 kg/kg (yttrium)
- Gross energy consumption: average 917 MJ/kg, range 311 (samarium and gadolinium) to 3 400 kg/kg (yttrium)

Lima et al. (2018) assessed the life-cycle impacts of producing 4 kg of rare earth oxides and 2 kg of co-products as a wet hydroxide from a Brazilian monazite ore. The results showed a large consumption of hydrochloric acid and ammonium hydroxide, as well as the production of radioactive waste of thorium and uranium, which influenced the impacts in all of the impact categories analysed. Electricity use contributed the most burden for the category of non-carcinogens, with almost 50% from the total of this impact category. Results from the analysis are shown in Table 4.4.

Table 4.13. Life cycle inventory data for production of 4 kg of rare earth oxides from Brazilian monazite ore.

	Quantity
Step 1: Monazite opening	
Monazite	9.84 kg
Sulfuric acid (93%)	15.36 kg
Ammonia (28%)	1.986 kg
Outputs from Step 1	
Thorium	394 g
Uranium	14.8 g
Silica	295 g
Step 2: Rare earth oxide production	
Hydrochloric acid (37%)	323 L
Ammonium hydroxide (25%)	299 L
Electricity	273 kWh

Source: Lima et al. (2018)
Note: "Monazite opening" refers to the initial grinding and extraction stage

It is not clear to what extent the data produced by Lima et al. are representative of the industry more widely. The large co-production of thorium and uranium, for example, is not typical of all REE ores: bastnäsite has a significantly lower content of radioactive elements. However, the data provide an illustration of the major inputs and outputs of REE ore processing and place a scale on associated energy use.

Marx et al. (2018) provide a comparative LCA of the production of neodymium-iron-boron (NdFeB) magnets using material mined at three sites, Bayan Obo in China as the world's largest site (both bastnäsite and monazite ores), Mount Weld in Australia (monazite ore) as the second largest and Mountain Pass (bastnäsite ore) in the United States (closed at the time that Marx et al. were writing, but since reopened). Mountain Pass is estimated to have the lowest environmental impacts due to improved handling of chemicals, and Bayan Obo the worst (over twice the normalised environmental impact of Mountain Pass). The most significant effect categories are freshwater ecotoxicity, human toxicity and marine eutrophication (noting, however, that the three sites are each at least 400 km from the sea). The superior performance of the Mountain Pass site is attributed to the effectiveness of measures such as recycling saline wastewater, cleaner production using a natural gas fired combined heat and power plant and the lack of a roasting process with associated emissions.

Deng and Kendall (2019) focused on production of heavy rare earth oxides from ion-adsorption clays (rather than monazite or bastnäsite) in the south of China. Results were in the range of previous studies that examined a range of ore types (greenhouse gas emissions of 258-408 kg CO_2e/kg mixed heavy rare earth oxide, primary energy consumption of 270-443 MJ/kg). Overall, it was concluded that the major impacts were attributable to mining and extraction due to the large quantities of chemicals involved in processing, of which ammonium sulphate was the largest contributor to many impact categories.

The LCA literature on recycling of rare earths is less extensive but growing. Binnemans et al. (2013) provide an early review of studies. The study makes a number of significant conclusions about the low rate of rare earth recycling, noting insufficient collection mechanisms, technical difficulties and lack of incentives in relation to the recycling of permanent magnets, nickel metal hydride batteries and lamp phosphors, and concludes that significant environmental and health benefits can be gained from recycling.

Sprecher et al. (2014) calculated the complete energy and environmental impacts of producing a kg of the rare earth metal neodymium for magnets by recycling computer hard-drives versus mining the same amount of virgin material. In the case considered, recycling had a human toxicity score more than 80% lower than mining and used almost 60% less energy. Recovery from other uses, such as use as a glass colorant, would require more resources.

Jin et al. (2016) also used LCA to compare new and recycled NdFeB (neodymium – iron – boron) magnets, indicating savings of 45% or more in environmental burden from recycling. Some differences in the properties of virgin and recycled magnets were noted, with the recycled magnet having slightly better properties.

Table 4.14. Life cycle impacts of producing 1 kg of virgin and recycled NdFeB magnets.

	Virgin	Recycled	Difference
Global warming as kg CO_2e	27	12	-56%
Acidification as H^+ moles eq	21	11	-48%
Carcinogens as benzene eq	0.069	0.035	-49%
Non carcinogens as toluene eq	249	136	-45%
Respiratory effects as kg $PM_{2.5}$ eq	0.12	0.059	-51%
Eutrophication as kg N eq	0.011	0.004	-64%
Ecotoxicity as kg 2,4-D eq	94	45	-52%
Smog (ground level ozone) as kg NOx eq	0.109	0.034	-69%

Source: Adapted from Jin et al (2016)

Summary of the risks of rare earth production and health

Although this section has placed much emphasis on the result of LCA, it is necessary to stress that the results of life-cycle analysis need to be treated with care. Although they are typically described as relating to “impacts”, in truth they represent “burden” or “hazard” instead. The latter terms have a relation to *potential* harm but require that individuals or other sensitive receptors are exposed to the substances in question. Impact should instead refer to estimates of actual harm to health and the environment (e.g. in terms of deaths, cancers, etc.), though quantification to these endpoints goes beyond LCA methods. To illustrate this point further, two workers at different sites may work with similar quantities of the same substances but will face very different levels of risk (and hence final impact) under different health and safety regimes. The use of protective clothing and equipment will go a long way to protecting workers, but such equipment is not always made available. Similarly, the actual risk associated with production wastes will vary according to how they are contained and treated. The high scoring for marine ecotoxicity given to the three sites considered by Marx et al. (2018) provides illustration of the need for care in interpretation of LCA outputs: each site is at least 400 km from the nearest sea, and hence extremely unlikely to have any noticeable impact on marine ecosystems. There are also questions concerning the validity of hazard scoring systems used in LCA studies, which require comparison of a large number of substances causing a range of different impacts. Many of these substances and effects have been little researched.

The LCA studies, however, are useful in highlighting that the production of refined rare earth metal involves the use of significant amounts of energy and of caustic and other hazardous substances in the processing of ores and refining of concentrates. The rare earths are hazardous in themselves, though naturally of variable toxicity. Pagano et al. (2016) report that adverse outcomes of REE exposures include a number of endpoints, such as growth inhibition, cytogenetic effects, and organ-specific toxicity, though acknowledge significant data limitations for all REEs except cerium and lanthanum. Extraction also leads to the liberation of other hazardous substances, including the radioactive elements thorium and uranium which tend to be left in mine tailings and other waste dumps.

Marx et al. indicate variation in environmental performance in production of NdFeB magnets at different sites of between a factor 2 and 3. Variation in burden arises from a number of factors:

- Risk management practices during production
- Risk management practices at the end of production
- The types of ore that are used, with different ores requiring different amounts of processing, the use of different reagents and quantities of reagent, and containing differing levels of hazardous substances, such as thorium
- The quality of ores, with respect to their rare earth content
- The energy systems that are in place, in relation to the fuels used and level of emission controls adopted.

Many of the worst examples of damage to health and the environment relate to unlicensed or illegal operations. However, these have been targeted by the Chinese authorities in recent years, for example through efforts to consolidate production into 6 major companies. The success of these efforts is not yet clear. There examples elsewhere also, for example around an RE refinery at Bukit Merah in Malaysia, where radioactive waste contaminated with thorium was dumped in the surrounding countryside (Jegathesan, 2012).

Several studies indicate significant life-cycle benefits of recycling. There is a clear focus in these studies on recycling rare earth magnets, and so conclusions should be considered indicative rather than demonstrating benefits of recycling across all rare earths in all applications.

Key areas that could provide a focus for policy concern:

- The adoption of efficient collection regimes and incentivisation of recovery, for example through extended producer responsibility.
- R&D on environmentally sound recovery and processing and dissemination of best practices.
- R&D on material use, substituting those Res associated with the highest impacts (where possible) and increasing efficiency of material use.

Promotion of “recycling” per se is likely to be insufficient, given that some techniques for recycling electronics lead to significant losses of rare earths as the components in which they are most concentrated are not separated out at the start of processing. The major barrier overall, however, still seems likely to be cost, noting that interest in rare earth recycling seems to have peaked shortly after prices increased dramatically in response to Chinese export controls.

A summary of the major burdens and impacts from primary and secondary production of rare earth metals is given in Table 4.6. These findings reflect the assessment of Schüler et al. (2011), who concluded that the recycling of REEs would provide significant benefits through reducing air pollutant emissions, groundwater contamination, acidification, eutrophication, greenhouse gases and release of radioactive materials.

Table 4.15. Summary of the major burdens and impacts of primary and secondary production of rare earths.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for illegal and unofficial mining. Potential for significant release of dusts, thorium and uranium. Substantial reduction in risk possible through effective regulation.	Not applicable.
Processing of ores and secondary materials	Significant use of caustic agents and solvents, potentially contaminating land and drinking water. Controllable via regulation.	High risk where informal processing is carried out, with particular concern over the dismantling and processing of e-waste. This may affect workers, their families and neighbours. Substantially lower relative to primary production in well-regulated environments.
Smelting	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Emissions can be closely controlled, both to air and water.	Similar types of impact to those from primary production. However, energy and other savings of around 50% seem achievable. This figure may rise as recycling technology advances assuming that recycling innovation keeps pace with developments in battery technologies.
Transport	Very largely dependent on proximity of operations to the Chinese centres of rare earth production for the foreseeable future.	Potentially significant given that there will be possibly few centres equipped for rare earth recovery, leading to the movement of secondary materials over significant distances, dependent on any barriers to trade that may exist.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, ore quality and fuels used, especially for power production.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment and advances in knowledge and optimisation of recycling technologies for the rare earths. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

Annex C. Cobalt

Extraction and reserves

Demand for cobalt is growing, especially as a result of its use in Li-ion (lithium-ion) batteries, including for electric cars. Bloomberg (cited by Transport&Environment, 2017) estimates a substantial increase in demand for cobalt for Li-ion batteries from less than 5,000 tonnes in 2016 to about 90 000 tonnes in 2030, an increase that by itself is only slight less than total current demand. Other uses include alloys for applications as diverse as orthopaedic implants and jet engines, industrial catalysts, pigments, radioisotopes for use in radiotherapy and electroplating. Cobalt prices increased by a factor 4 from 2014 to 2017 but have fallen back since.

The US Geological Survey estimates that global reserves of economically extractable cobalt are around 7 million tonnes, half of which is located in the Democratic Republic of the Congo (DR Congo) (USGS, 2018c). Most cobalt is found in deposits of copper and nickel and hence production of cobalt is closely linked to demand for these metals. JRC (2017) reports that 43% of cobalt is extracted with nickel, 32% with copper and 25% from primary cobalt operations.

Current production of cobalt metal is 110 000 tonnes annually, again, with more than half being mined in DR Congo, much of which is refined in China. Terrestrial resources amount to 25 million tonnes, and a further 120 million tonnes have been identified in manganese nodules and crusts on the ocean floors.

Li-ion batteries vary in the materials used to construct cathodes. Lithium manganese oxide (LMO) and lithium iron phosphate (LFP) batteries are considered the least environmentally problematic as they do not contain especially rare or toxic metals (Raugei and Winfield, 2019). However, batteries containing cobalt enable a higher energy density and hence have superseded LMO and LFP types. The most commonly adopted technology is currently lithium nickel-cobalt-manganese oxide (NMC) providing reliability and good energy density coupled with durability. Lithium nickel-cobalt-aluminium oxide batteries couple a higher energy density with slightly lower durability. Raugei and Winfield report on a further variant, lithium cobalt phosphate (LCP). There is thus consistent emphasis on the development of new battery types based around cobalt, indicating that non-cobalt alternatives seem unlikely to gain significant market share in the coming years, and hence highlighting the importance of maintaining supplies.

A challenge for manufacturing industry has been to ensure that supplies of cobalt are ethically sourced, given concerns raised over the use of slave- and child-labour in cobalt mining that have been extensively reported in the media[21,22] and by Drive Sustainability (2018). In DR Congo there are concerns about the fate of proceeds from mining in funding conflict. Traceability of cobalt to source, which would enable the supply to act in confidence that they are using ethically sourced material, is made difficult by weak rule of law and high experience of corruption in some important producer countries (Drive Sustainability, 2018) and the international nature of the trade, with mining operations in one country (e.g. DR Congo) and processing carried out elsewhere (e.g. China).

Recycled cobalt represented about 29% of US consumption in 2018. Cobalt was ranked eighth by Coulomb et al. (2015) in terms of critical raw materials subject to supply risk.

Cobalt and health

Cobalt is an essential human nutrient, as part of vitamin B12. B12 is involved in DNA synthesis, fatty acid and amino acid metabolism, the normal functioning of the nervous systems and the development of red blood cells.

At high exposure levels, however, cobalt can be harmful. The European Food Safety Authority (EFSA, 2012) has suggested an acceptable safe amount of 120 µg Co/day, whilst The United Kingdom Expert Group on Vitamins and Minerals concluded in 2012 that ingestion of cobalt-containing supplements up to 1 400 µg Co/day (in a 60 kg adult) was unlikely to produce adverse health effects.

The UK's Health and Safety Executive lists the following possible effects in workers (HSE, 2013):

- Short term vomiting and abdominal pain from ingesting cobalt salts
- Longer term effects include
    - Allergies (allergic dermatitis and asthma)
    - Inflammation and fibrosis of the lung in a condition known as "hard metal disease" which can become irreversible and lead to early death[23]
    - Cardiomyopathy
    - Possible enlargement of the thyroid gland

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[21] https://www.environmentalleader.com/2017/05/shortage-ethically-sourced-cobalt-congo-causes-trouble-ge-apple-tesla/

[22] https://www.theguardian.com/global-development/2018/oct/12/phone-misery-children-congo-cobalt-mines-drc

[23] Hard metal disease is most prevalent in occupations like stone cutting and grinding hard metal tools, and is less relevant to primary and secondary cobalt production processes.

- Experimental studies on animals have raised concerns of the following potential impacts:
    - Cancer, particularly lung cancer. IARC classification 2B, “possibly carcinogenic to humans”. Associated mechanisms indicate a threshold for action.
    - Effects on male fertility.

Similarly, CDC (2018) concludes that cobalt can harm the eyes, skin, heart and lungs and may cause cancer.

The potential for benefit or harm from cobalt exposure is of course dependent on dose. The Cobalt Institute[24] cites early work that established a link between cobalt and cardiomyopathy. Analysis considered individuals with a poor diet and very high alcohol intake from drinking large quantities of beer (which was also the source of the cobalt, which had been added to counteract the antifoaming effect of detergent residues on glasses). More recent studies of cobalt refinery workers (Linna et al., 2004; Lantin et al., 2013) and patients with hip implants containing cobalt (van Lingen et al., 2013) finds no evidence of cardiomyopathy.

Taking these factors into account, the effects of exposure to cobalt released by production processes on the general public should be negligible. The same applies to workers operating in well-regulated conditions. The same cannot be said for many workers in less- and un-regulated parts of the cobalt industry, particularly artisanal workers.

Cobalt mining and health

Like other mining activities, cobalt mining involves exposure to dusts and chemicals and the movement of large quantities of material, often utilising heavy machinery. As for production of any mined resource, examples of good and bad practice can be identified for cobalt. In countries where there is a strong regulatory environment, the risks of mining cobalt should be no greater than they are for other minerals.

In the case of cobalt, by far the main producer is DR Congo, where working conditions in the industry have come under sustained criticism. Particular problems relate to the hazards of artisanal mining (mining by hand) (Amnesty International and Afrewatch, 2016) and the use of child labour. DR Congo government figures indicate that 20% of cobalt in the country (roughly 10% of global production) is produced from small mines. It is estimated that there are up to 150 000 artisanal miners in the area, including approximately 40 000 children (UNICEF estimates) who wash and sort ore before it is sold.

Legislation in 2002 sought to regulate artisanal mining, creating official artisanal mining areas where regulations could be better enforced. Workers in these areas are required to hold valid “artisanal mining cards”, issued by the provincial government, to sell their produce to licensed traders and respect the “Code de conduit pour

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[24] https://www.cobaltinstitute.org/cobalt-and-heart-disease.html.

l'exploitant artisanal" regarding "safety, health, use of water and the protection of the environment".

However, most workers operate in unauthorised and unregulated areas or trespass on land controlled by industrial mining companies. Some workers mine underground, others dig for cobalt in discarded mine tailings. The resources available to these miners are generally of poor quality, and this, combined with the unsophisticated extraction techniques, leads to low productivity and income. Underground mines tend to be unventilated, leading to high dust levels, and are prone to collapse. During the writing of this report a mine owned by the Kamoto Copper Company[25], a subsidiary of Glencore, in DR Congo collapsed, killing an estimated 36 workers[26]. The company stated that there are daily intrusions to their concession by 2,000 miners per day, presenting "a significant risk to the company's employees, operating equipment and the illegal artisanal miners themselves". However, permitted and unpermitted/illegal operations appear to coexist with only limited effort being made to close down illegal activities.

Amnesty International found that very few of the artisanal workers take basic safety precautions. Given the unregulated nature of the industry, there are no available statistics on accident rates and incidence of ill health.

Health risks from collecting cobalt for secondary production, and initial processing

Similar issues arise for cobalt as for the collection of copper and rare earths for secondary production from waste materials. First, it is essential that efficient collection schemes are in place to enable a significant level of recovery. Then it is necessary that safeguards are in place to ensure that those materials are delivered to locations where workers are properly equipped to handle the wastes.

As noted above, there is a substantial growth in demand for cobalt from the automotive battery sector. Efficient systems for recovering lead-acid automotive batteries are already in place and suggest that systems with a similar level of efficiency can be developed for Li-ion batteries also, over time. ILA (2015) reports the recycling of more than 99% of lead from lead-acid batteries in Europe and in the USA27. Major factors for this high recovery rate are the value of the lead in car batteries at the end of their useful life and ease of recovery. Legislation has also played an important role. The infrastructure that is in place for collection of lead can be extended to recovery of materials from lithium-ion batteries in the automotive sector. Subsequent processing steps are more sophisticated for Li-ion batteries than lead-acid, but the high value of the materials present and limitations on supply from primary sources can be expected to stimulate the sector. Efficient collection systems should also be in place for other cobalt applications in aviation, medical appliances and industrial catalysts. Recycling activities for these products, where possible, can

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[25] The company extracts both cobalt and copper at the site.

[26] https://www.bbc.co.uk/news/world-africa-48797845

[27] Eurostat (2019) reports EU recycling rates for lead-acid batteries that are lower, though still typically >80% in the EU. The disparity to the ILA data reflects differences in methods, with the Eurostat data based on sales and recovery in individual years.

be expected to take place under controlled conditions, creating limited risk to workers.

The Eurostat data also show that the recycled lead content of lead-acid batteries is in excess of 85% in all countries, indicating a near ‘closed system’ for the lead content of these batteries. Whilst it will clearly take time for recyclers to have both the secondary material available and capacity to enable Li-ion battery manufacturers to attain a similar position, it is a clear possibility in the medium term for the automotive sector so long as the economic case and legislative basis for recycling remains strong. This then has implications for the impacts associated with both primary and secondary production of cobalt, lithium and other metals.

The recycling of Li-ion batteries in other consumer applications seems likely to be more problematic given less systematic collection systems and difficulties in extracting the batteries from electronic and other items. As was the case for the REEs, separation of electronics into their component parts to remove Li-ion batteries is time-consuming and resource-intensive. Mechanical shredding leads to significant loss of material (Sprecher et al., 2014), whilst dismantling is labour intensive and exposes workers to additional risk. However, in recognition of the value of the materials that they contain there is growing interest in the concept of ‘urban mining’ of wastes, for example through the Urban Mine Platform28 covering the EU, Switzerland and Norway.

The distinction between automotive batteries and those used in other applications is not absolute. There is active investigation into the possibility of repurposing automotive batteries once storage capacity has declined to a sub-optimal level for use in vehicles, for grid-connected energy storage. Neubauer et al. (2015) indicate that automotive batteries are likely to retain 70% of their initial capacity at the end of the service life of the original vehicle and once adapted could be used as storage for the electricity grid, for example to provide peak-shaving services. Under likely conditions of use it was considered that second use battery lifetimes would be a further 10 years beyond their use in vehicles. Use in dedicated storage facilities would facilitate entry to recycling systems at the end of their second useful lifetime. Dispersed use, for example in the domestic market, would seem to increase the likelihood of less desirable forms of disposal, such as landfilling, depending on the residual value of the batteries and the local legislative framework on battery disposal.

Primary and secondary cobalt production processes, and their burdens

Processing is carried out using different methods for different types of ore[29], depending on their composition and physical and chemical characteristics (JRC, 2017; Farjana et al., 2019). The following provides an overview, but it is acknowledged that it is not comprehensive.

- Hydrometallurgical methods include pressure acid leaching and solvent

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[28] http://www.urbanmineplatform.eu/homepage.

[29] Cobalt is usually extracted with copper or nickel ore, though some cobalt ores such as erythrite and skutterudite are also exploited.

extraction.

- Electrowinning where materials are filtered, heated and electrolysed, during which the cobalt precipitates onto stainless steel, forming high purity metal.

- Vapometallurgy, involving the vaporisation of ore using carbon monoxide and other gases., before passing the gas stream to a separate chamber to deposit the cobalt.

- Pyrometallurgy involves heating ore to separate metals based on their specific characteristics such as melting point and density.

- Roasting of cobalt arsenide ores to drive off the arsenic.

- Biological methods using bacteria to leach cobalt from ore.

- Direct recycling.

Figure 5-1 provides a flow diagram for the production of copper and cobalt from ore. The system shown is illustrative and will not apply to all production processes (see, e.g., Dai et al., 2018 for an alternative). Reference to Figure 2-1 shows the general types of impact at each stage.

Each of these processes will generate its own set of hazards for human health, for example (acknowledging that, given the diversity of approaches available, this list is incomplete):

- Release of dust during mining and grinding operations

- Generation of acid and organic solvent wastes

- Emissions of volatile organic compounds (VOCs)

- Liberation of arsenic and arsenic compounds

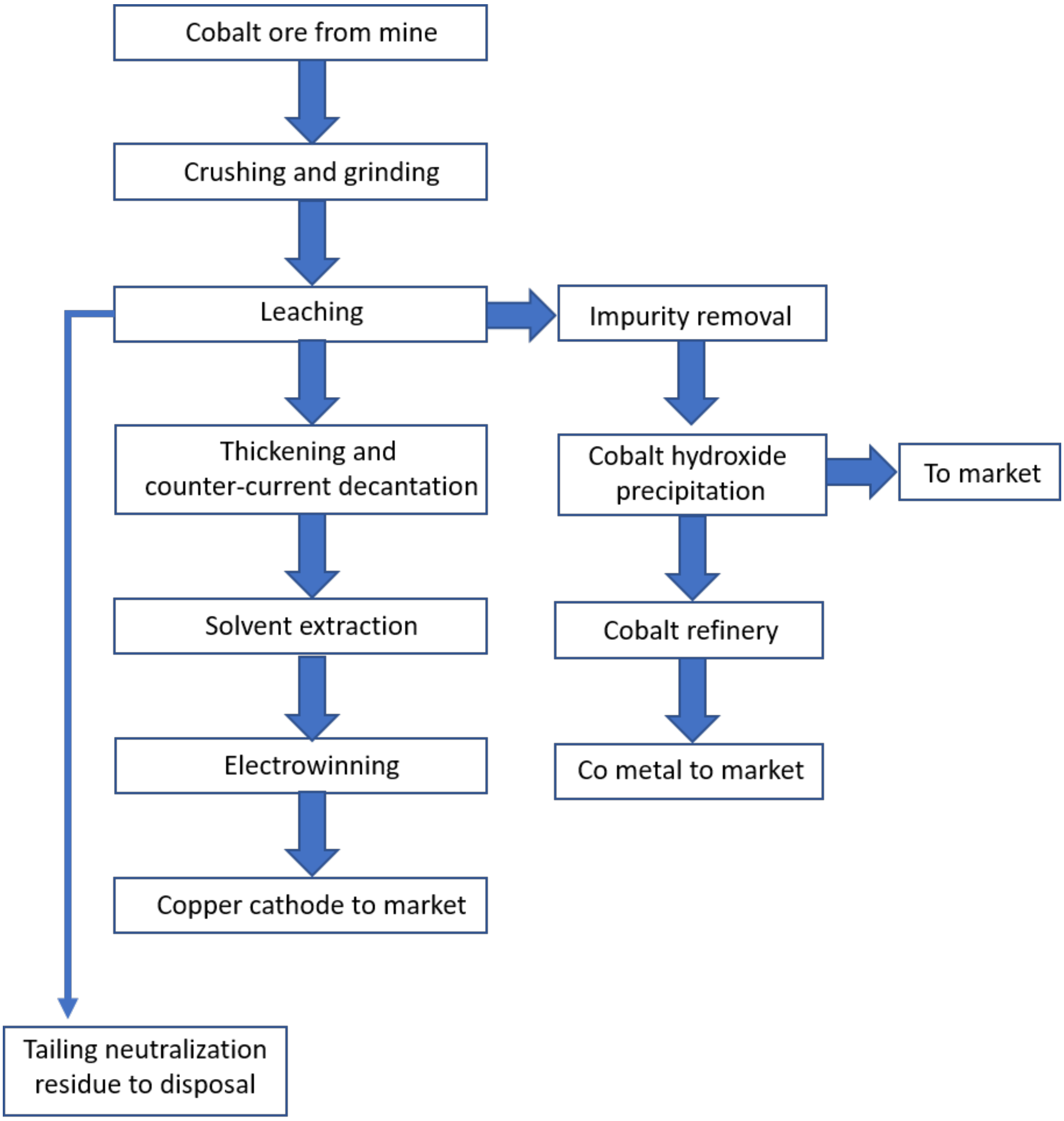
- Emissions from energy use throughout the process, from mine to smelter

- Waste production

- Chemical hazards for workers

- Physical hazards for workers

Figure 5-6. Illustration of copper and cobalt metal production from copper-cobalt ores

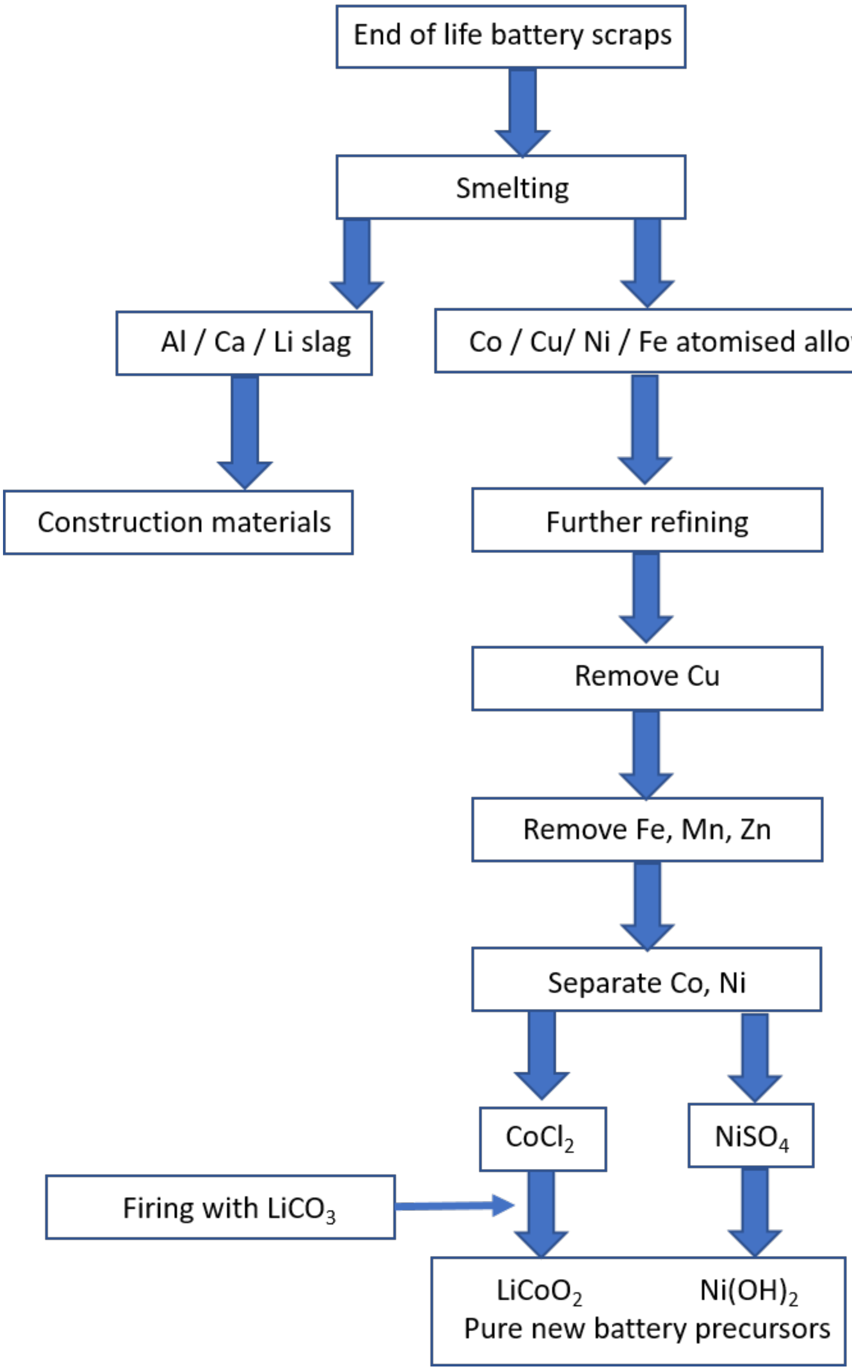


As discussed previously for copper and the REEs, the impacts that arise from these hazards will be a function of several factors, including the regulatory environment and the composition of the power generation sector.

Recovery from secondary sources can occur through the introduction of the recycled material at an appropriate stage in a primary refining or transformation process, with final products being in the form of cathodes, powders, oxides, salts or solutions, depending on the needs of the subsequent market (JRC, 2017).

An illustration of recycling processes, taking the example of the recycling of materials in lithium-ion batteries at a plant run by Umicore in Belgium, is shown in Figure 5-2. This system is designed specifically to produce new materials for the batteries market, rather than pure cobalt. Opportunity is taken during the process to extract other useful materials such as copper, iron, manganese and zinc, and construction materials.

Figure 5-7. Overview of the recycling process for lithium-ion batteries at Umicore



Source: Adapted from Yazicioglu and Tytgat (2011).

Life cycle analysis and associated health impacts

The focus of many LCA studies concerning cobalt is the production of Li-ion batteries, in recognition of the likely expansion of this market in the years to come as electric vehicles become the norm. Of interest here, as elsewhere in this report, is not the comparison of burdens to health and the environment over the full life cycle but specifically the burdens associated with production of battery cells from virgin and recycled materials.

Dewulf et al. (2010) compared recycling of Li-ion batteries with production from virgin material. Recycling was found to result in a 51% saving of natural resources through reduced dependency on mineral ore extraction and reduced energy demand, comprising a 45% reduction in fossil fuel use and a 57% reduction in nuclear energy demand. Results are clearly sensitive to the energy mix assumed for the analysis.

Yazicioglu and Tytgat (2011) provide results for LCAs comparing the manufacture of battery cells using nickel and cobalt from ore and from battery recycling. They found a 70% reduction in both energy use and greenhouse gas emissions when following the recycling route. System boundaries covered all processes from obtaining materials through to assembly and filling of the battery cells.

Raugei and Winfield (2019) provide analysis of various Li-ion batteries. Their LCA found that the cumulative energy demand of the battery pack was dominated by the "embodied" energy in the input materials for the cathode, including cobalt. Recycling involved manual dismantling, mechanical shredding and a hydrometallurgical recovery process, selected as it is less energy intensive than pyrometallurgical techniques. Results indicate that the overall production of greenhouse gases is reduced by the recovery of materials, but only by a relatively small amount (up to 8%). Raugei and Winfield compared their results with those from other studies and found a high degree of variability, with assumptions on the underlying energy mix for production being a critical factor.

Farjana et al. (2019) provide LCA of the cobalt extraction process and conclude that fossil fuel consumption provides the greatest environmental impacts, though notes also significant impacts linked to blasting and to the composition of the cobalt ores and their association with toxic metals leading to exposure to dusts containing arsenic, cadmium and manganese as well as cobalt itself. Results for the impact categories relevant to health are summarised in Table 5.1.

Table 5.16. Major health impact categories in LCA of cobalt extraction.

Impact categories	Contributing activity	Harmful emission from activity
Global warming	Electricity	CO_2
Human toxicity – cancer	Electricity, blasting, cobalt particles	Cadmium, cobalt
Human toxicity – non-cancer	Electricity, cobalt particles	Arsenic, manganese

Source: Adapted from Farjana, 2019

Concerns raised about the welfare of workers in the cobalt industry of DR Congo to the extent that they are not related to exposure to hazardous substances are outside the scope of all of these LCAs, which (like LCAs more generally) deal only with material flows.

Summary of the risks of cobalt production and health

Significant risks have been identified for cobalt mining in DR Congo, the dominant supplier. The worst impacts often occur to, and are blamed on, artisanal workers who lack basic safety equipment. However, given high levels of child labour, it is clear that there are serious problems in regulation of the sector in the country.

Occupational health risks of secondary cobalt production could be lower per unit of metal recovered than for either copper or rare earth secondary production. At the collection phase for automotive batteries (the dominant use of cobalt in the coming years), risks should be limited given that the necessary infrastructure already exists in most, if not all, countries, in terms of the vehicle scrap industry (acknowledging that systems vary in their sophistication). Removal of the batteries from vehicles should be straightforward, and certainly not more hazardous than other vehicle dismantling operations. Reprocessing will require specialist facilities, reducing the potential for workers operating under basic conditions to take on the work beyond collection of material.

The current performance of vehicle scrappage facilities creates the opportunity for high levels of collection and recovery, possibly at the level of the “near-closed loop” for automotive lead-acid battery where more than 99% of batteries are recovered in Europe and the USA and the recycled lead content of new batteries is in excess of 85%. The most pressing concern is for recycling capacity to keep pace with the amount of Li-ion batteries that will need to be reprocessed in the coming years. Intervention may be appropriate if the price obtained for recycled material is insufficient to stimulate the recycling industry on a timescale that avoids significant waste of resource.

Other major parts of the cobalt waste stream with respect to aviation and industrial catalysts should, similarly, be controlled by enterprises who are set up to exploit the materials that they receive in a safe and regulated manner.

One important waste stream is less controlled at present: the use of cobalt in Li-ion batteries for consumer products. Removal of batteries through dismantling involves hazards through exposure to possibly harmful substances and physical risk. The solution is to make it easy to remove components from goods, which would also facilitate repair.

Burdens and impacts of primary and secondary cobalt production are summarised in Table 5.2.

Table 5.17. Summary of the major burdens and impacts of primary and secondary production of cobalt.

	Primary production	Secondary production
Mining	High risks where regulatory structures are either absent or poorly implemented. High risks for illegal and unofficial mining with particular concern over. Substantial reduction in risk possible through effective regulation.	Not applicable.
Processing of ores and secondary materials	Significant use of caustic agents and solvents, potentially contaminating air, land and drinking water. Release of arsenic compounds from some cobalt ores. Controllable via regulation. Energy use, generating emissions to air.	Lower burdens relative to primary production in well-regulated environments.
Smelting	Emissions to air from power generation and fuel use (SO_2, NO_x, PM_{10}, CO_2). Emissions of the pollutants most damaging to health can be closely controlled, both to air and water. Greenhouse gas emissions are controllable partly through efficiency measures and more extensively through the use of low-carbon/carbon-free energy alternatives.	Similar types of impact to those from primary production. However, savings of energy are achievable, though some evidence indicates that these are likely to be modest, less than 10%. This figure may rise as recycling technology advances.
Transport	Significant transport distances from DR Congo to main processing sites in China.	Potentially significant given that there will be possibly few centres equipped for reprocessing new types of battery, leading to the movement of secondary materials over significant distances.
Overall burdens	Substantial variation in overall burdens through differences in the regulatory framework and enforcement, the type and quality of ore used. and fuels used, especially for power production.	Significant variation possible, again through differences in regulatory framework and enforcement and fuels used for power production.
Trends	Increasing burdens as ore grades decline. Reduced burdens through advances in the regulatory environment.	Reduced burdens through advances in the regulatory environment and advances in knowledge and optimisation of recycling technologies for cobalt. Increased burdens where secondary materials are exported to countries that lack efficient processing infrastructure.

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