ENGLISH VERSION

Challenges for Meeting Increased Demand for Metals and Minerals

A component report of the IVA's *Roadmap for Metals and Minerals* project

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1. Foreword

»A reliable supply of metals and minerals is essential to manage the transition to a fossil-free society.«

A reliable supply of industrially strategic metals and minerals is essential to maintain and develop our high-tech industry and to manage a successful transition to a fossil-free society. As fossil fuels are phased out, demand for metals and minerals is expected to grow significantly, given their essential role in increasing electrification and digitalisation. Key mineral resources and value chains are currently controlled by a few countries outside the European Union (the EU), such as China, Russia, Brazil, the Democratic Republic of the Congo and South Africa. This increases vulnerability and poses a risk of hindering industrial development in the EU. As a significant European mining nation, Sweden can therefore play a crucial role in the EU's future supply of metals and minerals.

The purpose of the IVA's Roadmap for Metals and Minerals project is to help Sweden and Europe secure long-term, sustainable access to the metals and minerals needed for the transition to a fossil-free society and increased competitiveness.

This is the first of four reports within the Roadmap for Metals and Minerals project. The other three reports are 'Circular Flows to Meet Increased Demand for Metals and Minerals', 'Increased Demand for Metals and Minerals – Conflicts of Objectives and Interests' and the synthesis report 'Metals and Minerals for Sustainable Development and Increased Competitiveness'.

This report focuses on describing the value chains in the supply of metals and semi-finished products that will be crucial in the production of the new technologies that will be required to meet climate goals and build sustainable societies.

The goal is to describe important supply chains for industry in an educational way, to highlight weaknesses and to discuss how these can be strengthened. There is a brief description of the technical processes required for the different stages of production. The intention is not to provide detailed technical descriptions, but to illustrate the magnitudes and contexts involved, so as to create an understanding of the challenges involved in achieving climate goals.

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Stockholm, February 2024

Magnus Ericsson
Expert Group Chair

2. Summary and conclusions

»Demand for metals and minerals will increase significantly. As a well-established mining country with multi-faceted mining expertise, Sweden can play an important role in meeting that demand.«

This report within the *Roadmap for Metals and Minerals* project is summarised in a series of observations on the baseline criteria and the challenges. It also addresses the measures required to secure access to the metals and minerals that will be needed to manage the transition to a fossil-free society. The report's facts and conclusions form the basis for the project's synthesis report *'Metals and Minerals for Sustainable Development and Increased Competitiveness'*, which will provide recommendations to decision-makers in various sectors.

Criteria to address

Demand for metals and minerals will increase significantly at a global level. Recycling and resource efficiency improvement are not enough to meet future needs.

- The transition to a fossil-free society, coupled with digitalisation, population growth and improved living standards, is increasing global demand for metals and minerals. This demand encompasses not only traditional metals like iron (steel), copper and aluminium, but also those that have not yet been used extensively, many of which fall into the EU's 'critical' classification.

- Global demand for traditional metals, such as iron (steel) (2,000 Mt/year), aluminium (70 Mt/year) and copper (20 Mt/year), differs significantly from demand for most of the critical raw materials. That is on a completely different scale; for instance, rare earth elements (REEs) (200,000 t/year), cobalt (150,000 t/year) and platinum-group metals (400 t/year).

- Due to the speed of technological development, there is significant uncertainty as to which critical raw materials will be in demand in the future. A high degree of flexibility is needed in order to respond to rapid fluctuations in demand. While the demand for traditional metals is expected to increase steadily, following the trend of the last half-century, demand for critical metals and minerals is projected to accelerate rapidly, albeit from relatively low levels.

- As demand increases, larger and larger volumes of all these raw materials, critical as well as traditional metals and minerals, are being incorporated into various products, paving the way for increased recycling. However, the supply of recycled materials is always based on the smaller volumes that were produced historically, and hence cannot even theoretically cover future needs as long as demand increases. In addition, it is neither technically nor economically feasible to achieve 100% metal recycling.

We are facing a geopolitical reality that creates new risks in the global supply chains of metals and minerals.

- In geopolitical terms, access to and control of metals and minerals is becoming increasingly important, both economically and in terms of security. This is particularly true for the EU, which relies heavily on imports, and is evident in the growing tension and intensified technology race between the United States (the USA) and China, coupled with their aim to establish strategic partnerships with individual countries and regions. This new reality has implications for existing trade flows, leading to an elevated risk of disruption to metal supplies. As a result, an increasing number of companies that are dependent on critical raw materials are entering into cooperation agreements with mining producers to secure direct access to their requirements.

- Chinese companies dominate the smelting and refining stages in the production of many critical metals and also play a significant role in mining several critical metals and minerals, including rare earth elements (REEs) and graphite. At the same time, China relies heavily on imports of base metals. In addition, Chinese companies' ownership and control of mines and mineral deposits outside China has increased rapidly, albeit from a relatively low starting point.

- Legislation and government support for national value chains for critical raw materials outside the EU, such as the US Inflation Reduction Act (IRA), are already diverting new investment from the EU to other parts of the world. Every factory for electric cars, solar cells or batteries not established in Europe represents a missed opportunity to enhance skills, knowledge and resources, instead redirecting them elsewhere. The long-term consequences of this development are challenging to assess, as they may lead to indirect effects and influence the dynamics of where future innovation occurs globally.

Swedish mining expertise, characterised by high sustainability standards, offers a competitive advantage on the international stage.

- Sweden possesses substantial mineral resources, with active exploration and mines producing iron ore, base metals and precious metals that are hugely significant for the country and for the EU. In addition, Sweden has documented deposits of several critical metals and is a major exporter of metals and minerals both to the EU's internal market and beyond.

- From an international perspective, Sweden's energy system has a small climate footprint with almost fossil-free power generation. This provides a foundation for participants in mineral extraction and processing to establish fossil-free value chains. However, a challenge lies in the substantial investment needed for the new electricity-generation capacity and infrastructure that will be needed to manage the sharp increases in future demand that are anticipated.

- Sweden's mining 'cluster' consists of world-leading mining companies, smelters, consulting firms and suppliers of mining equipment, as well as advanced research-and-development resources at universities, professional organisations and companies. In addition, the Swedish state is a long-term player through the iron-ore producer, wholly-owned LKAB.

- In Sweden, sustainability is highly prioritised, and both industry and the government make substantial investment in research and innovation. This places companies at the forefront in terms of efficient technical solutions and sustainable production, providing them with competitive advantages in the international market.

- The interdependence between mines and mining-equipment manufacturers has been, and remains, a key competitive advantage. Equipment manufacturers are as important to the Swedish economy as the country's mines, and the two sectors are intimately linked.

Challenges to manage

Key value chains from prospecting and mining to smelting are threatened by a lack of capital, skills and knowledge.

- Europe was the dominant mining region at the dawn of industrialisation in the 19th Century. Since then, it has lost importance and now accounts for only about 3–4% of the world's mining production. Today, only 3.3% of total global exploration expenditure goes to the EU, of which just under 1% is spent in Sweden.

- It is feasible for Sweden to produce several of the critical metals and minerals required in the EU for increased electrification and digitalisation. However, exploration has not been specifically targeted towards these raw materials, and additional efforts are needed to increase knowledge about their occurrence and the processes involved in locating, extracting and refining them.

- Virtually no new smelting or metal-refining capacity is being built in the EU. Instead, the focus is on expanding and developing existing facilities, based on conventional technologies for the extraction of base- and ferrous metals. The new facilities needed to produce the critical raw materials, as well as increasing the output of traditional metals, require a large investment. In addition, there are difficulties with high energy costs and complex permitting processes. Sweden’s Hybrit and H2 Green Steel (H2GS) are examples of how European companies are trying to develop new processes for extracting metals.

- There is a substantial lack of both knowledge and facilities for the critical raw materials. Metallurgical expertise for critical raw materials is available in the EU up to a point, but coordinated, focused initiatives in research and innovation are required, as well as investment in new facilities, if future needs are to be met.

- Sweden has no mineral-technology laboratories or pilot facilities equivalent to those in Finland (Metso and GTK) and Norway (Sintef/NTNU). Nordic cooperation needs to be developed in this area.

- Environmental assessments of new mines and smelters are intended to reduce their environmental impact and balance different societal interests. This often involves difficult trade-offs, which can be perceived as an obstacle to the establishment of new facilities. It is in everyone's interest to make the processes as time-efficient and predictable as possible. See also the project's report *'Increased Demand for Metals and Minerals – Conflicts of Objectives and Interests'*.

Europe faces major competitiveness challenges relative to many mineral-rich countries.

- Mining and metal-production costs in the EU are higher than in many other mineral-rich regions, such as Africa and South America. This is true regardless of the metal or mineral. European mines and smelters have higher costs for labour, energy and input materials. In addition, requirements for good working conditions and minimal environmental impact are more stringent than in many non-EU countries.

- The market for metals and minerals is global. Europe’s mining industry is competitive but must remain efficient and innovative to maintain its competitiveness. Sweden’s mining ‘cluster’ (as described above) is well-placed in this respect, providing a good foundation for continued competitiveness.

- Future mining projects in Europe must remain competitive. It is economically questionable to set up mines solely to ensure the security of supply, which would imply the need for substantial subsidies and a loss of efficiency. Any investment in new mines in the EU for geopolitical reasons will require careful analysis.

- Just having operating mines is not sufficient to ensure the supply of metals and minerals. Access to various processing steps is also crucial, including the capability to produce pure metals in smelters and refineries, as well as critical semi-finished products like batteries or permanent magnets. These process industries are highly capital-intensive and demand specialised skills.

Actions to take

New partnerships with mineral-rich countries around the world will be needed in order to secure Europe's supply of metals and minerals.

- Europe cannot rely on a well-functioning global market to meet its needs. To reduce the vulnerability of its supply chains, the EU should enter new strategic partnerships with countries, both within and outside Europe, that have either mineral resources, refining processes, or the production of strategic components.

- As one of Europe's most important mining countries, Sweden should actively work to create better conditions for producing metals and minerals. It can learn from leading mining countries such as Canada and Australia that have similar conditions and challenges to Sweden's, but also have aggressive strategies for securing their supply and their role in the market.

- Africa has significant resources of metals and minerals. Sweden and the EU should increase their cooperation with African countries to secure access to critical metals and minerals, and to strengthen the economies of mineral-rich countries. African initiatives such as the planned economic zone for battery raw materials and components (a collaboration between Zambia, the Democratic Republic of the Congo and the African Union) deserve Swedish and European participation. Swedish and European support is also needed for the production of so-called conflict minerals (tin, tantalum and tungsten) in Africa, of which several are currently classified as critical by the EU.

Increase knowledge of China's resources, needs and strategies.

- China is a dominant force in the world's supply of critical raw materials. At the same time, the country is highly dependent on imports of many traditional metals and minerals. This situation should form the basis for EU and Swedish strategies to strengthen the security of supply. Deeper knowledge and facts are needed regarding Chinese mining companies and their expansion outside China, as well as the governmental support to these mining companies that partially disrupts market forces. Increased knowledge of China's mineral dependency and mineral policy would help Sweden and the EU formulate their raw-material policies based on facts about Chinese and European needs and requirement criteria.

Develop methods to better integrate enhanced sustainability practices in the mining industry. This can also contribute to increased competitiveness.

- Mines, mineral-processing facilities and smelters affect not only the natural environment and climate, but also socio-economic conditions. At the same time, the Swedish mining industry is also a link in a global supply chain. This means that conflicts of interest arise at several levels where, for example, the environmental impact is local, but the climate impact is global.

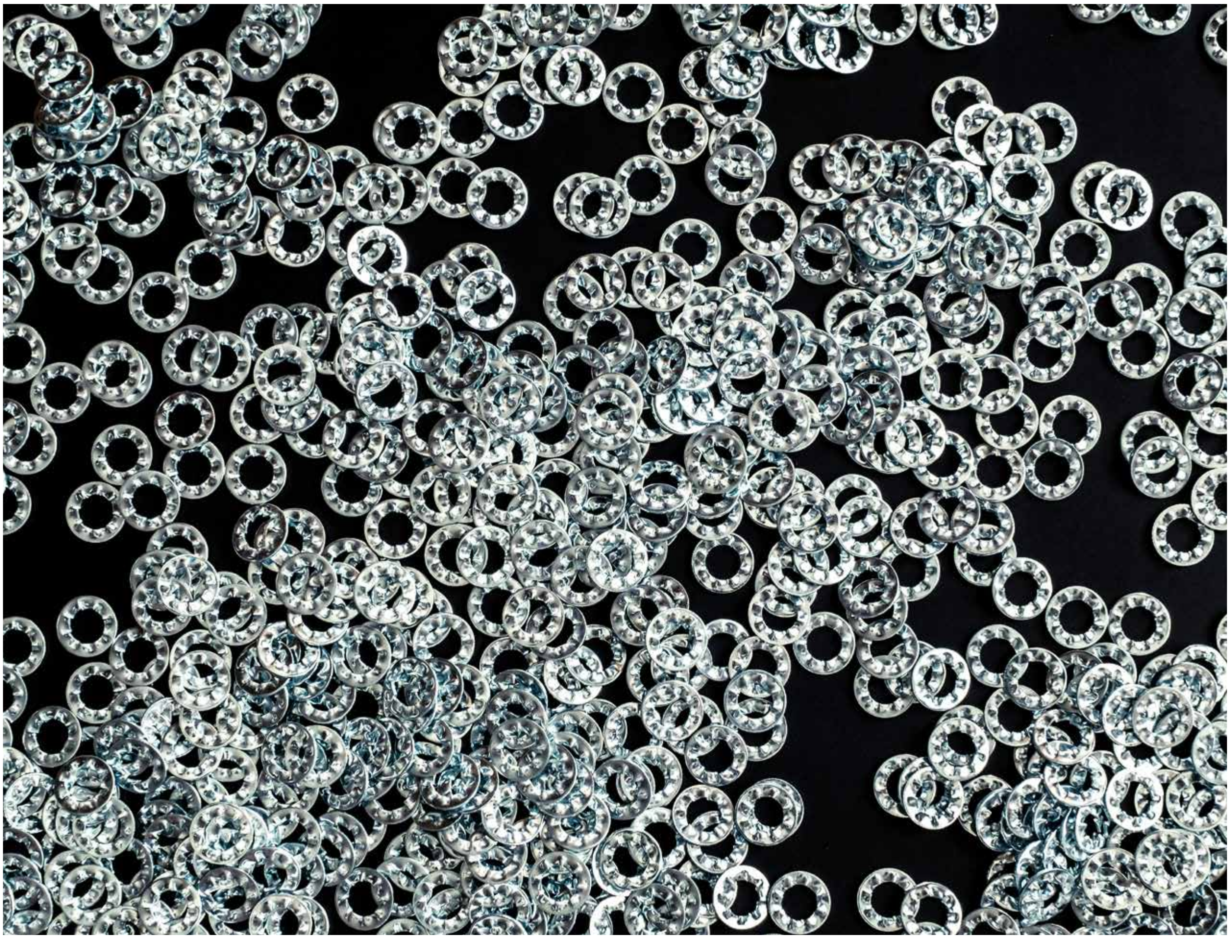
- When planning new mines, a holistic perspective needs to be taken on the entire life cycle of the mine to minimise the environmental impact, both during operation and after the mine has been closed. Many companies are already doing this, but the method needs to be improved and applied not only in Sweden but throughout the EU — and the world.

- There is a trend towards electrification and digitalisation, and the introduction of remote-controlled autonomous work vehicles, as a means of reducing environmental impacts and increasing the safety of mine workers. Machines can thus be safely operated remotely from a control room.

- There needs to be a better understanding of the importance of the mining industry for reduced climate change, increased competitiveness and improved welfare. Research and innovation are required in order to identify such approaches and thought models, along with collaboration among the various stakeholders that include mining companies, equipment suppliers, academia and the authorities.

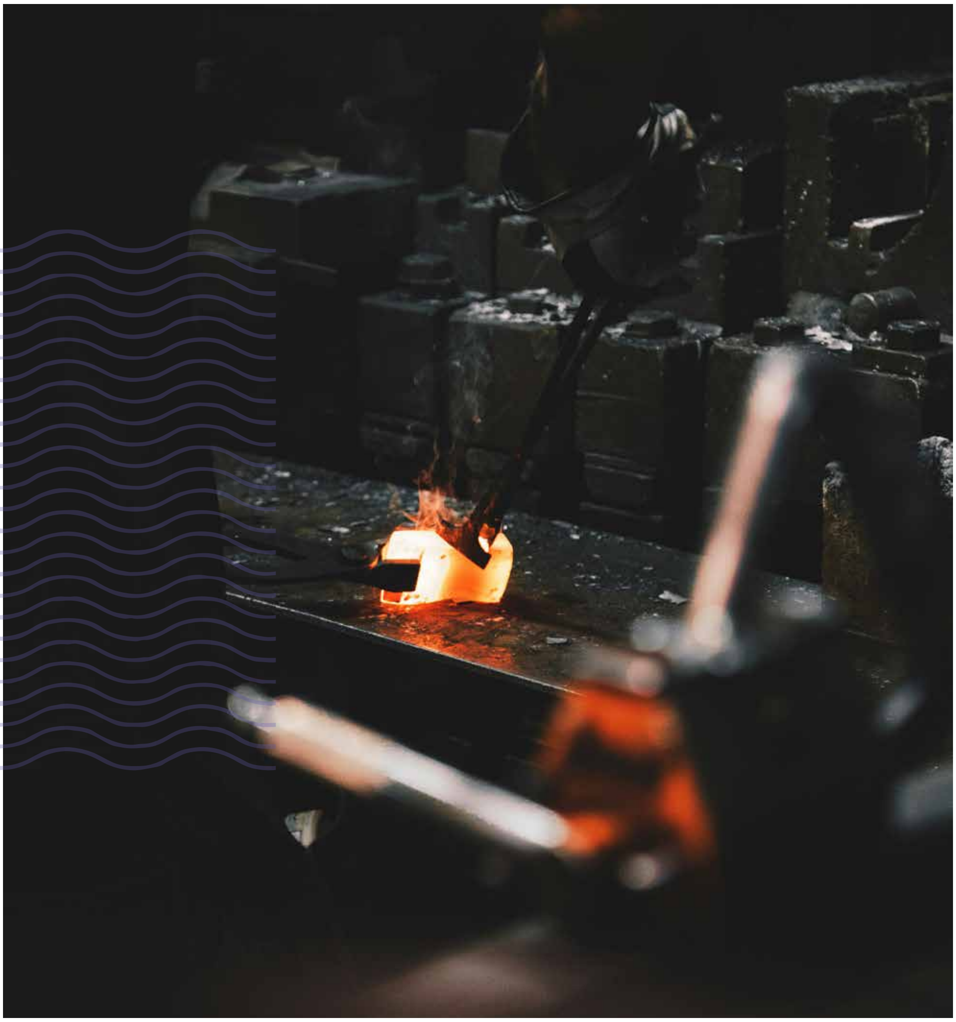
Increased competence, research and innovation are needed at all stages of the value chain.

- Swedish competitiveness in the mining industry must be strengthened by increased ambition in research and innovation. Collaborative research has played an important part in increasing the competitiveness of Swedish mining, but it takes



too long to go from ideas to practical applications. Efforts are needed for innovative exploration, processing, extraction and refining, with a particular focus on the critical metals that are required for a green transition. The mining and minerals industry needs access to research funding for both fundamental and applied research.

- In addition to technical aspects, developed social-science research is needed for an active mining industry, focusing on environmental and socio-economic conditions, including land use and permitting.
- Resource efficiency and recycling are other parts of the value chain where research and development efforts are extremely important. There are too few processes and methods for extracting critical metals, both from mines and from various types of scrap. Much of the expertise required to manage the entire value chain for these metals is also lacking today. Product design for increased resource efficiency and simplified recycling are other areas where intensive research should be initiated. This is covered in more detail in the project's report 'Circular Flows to Meet Increased Demand for Metals and Minerals'.



3. Glossary and the periodic table

This provides explanations of many of the technical terms used in this report.

Base metals
Metals with very broad applications. Usually refers to copper, zinc, lead, nickel and aluminium.

Battery metals
An unscientific grouping of materials used in batteries. Usually refers to the metals lithium, cobalt, vanadium, manganese and nickel, and the mineral graphite.

By-product metals
Metals extracted as by-products during the processing of ores containing 'main' metals (see below).

Cobalt
A transition metal mostly used in combination with other metals. Used mainly in batteries, but also in alloys, carbide tools, magnetic materials and some chemical processes.

Concentrate
Enriched mineralisation recovered after the initial mineral processing of an ore.

Critical raw materials/metals
Raw materials with significant risk of supply disruptions that may have undesirable consequences. In the EU, raw materials are given this classification because of their economic importance in relation to their supply risk. Examples of critical metals in the EU are cobalt, lithium, manganese and rare earth elements. The EU's list of critical and strategic raw materials is updated every three years, most recently in 2023 (see also Chapter 9).

Electrometallurgy
High-temperature melting of metals using electric power, usually in electric-arc or induction furnaces.

Flux
A substance added to a melt to lower its melting point and make it more fluid.

Gangue
See waste rock.

Graphite
A mineral consisting of the element carbon that exhibits both metallic and non-metallic properties.

Hydrometallurgy
The extraction of metals using chemical solutions and water-based processes, sometimes also by means of electrolysis.

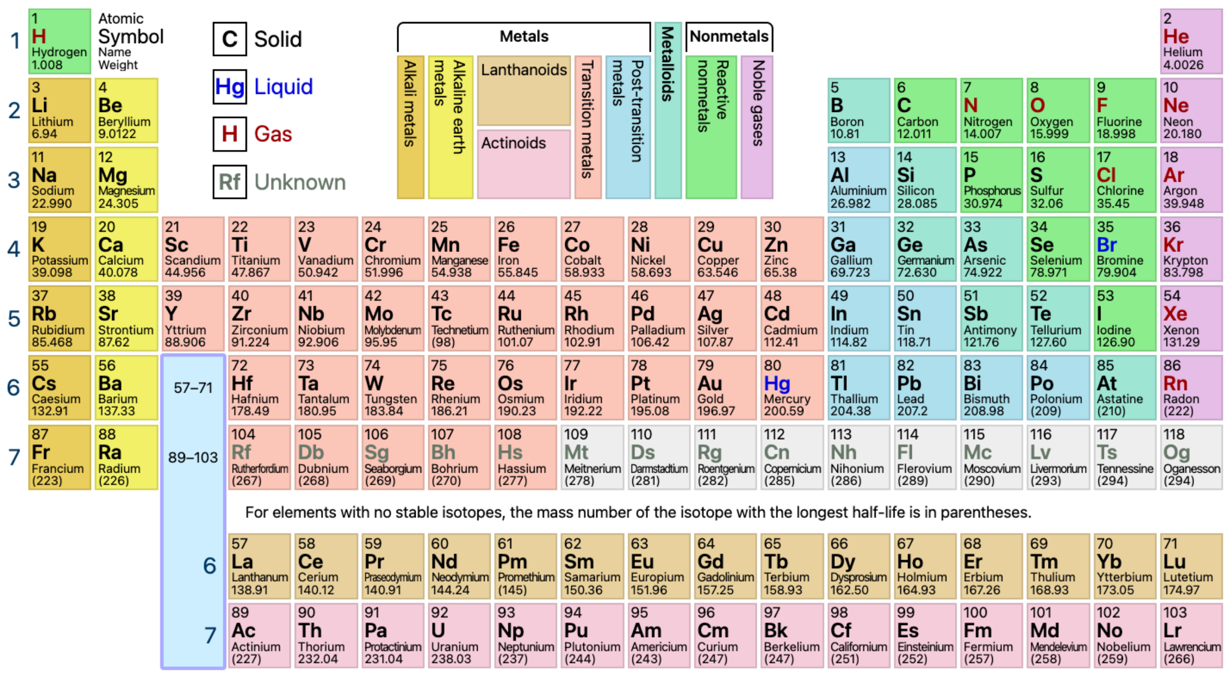
Industrial mineral
Anything extracted from the earth's crust except energy minerals, metal ores, water and gemstones. Examples of industrial minerals include graphite, quartz and limestone.

Junior companies
Companies involved in prospecting and exploration, but with no revenue from existing mines. Operations are often financed by venture capital.

Lithium
The lightest of all metals. Has high electrochemical reactivity and is mainly used in batteries.

Main metals
The metals in an ore that are the most profitable (cf. by-product metals).

Figure 1: The periodic table: a classification of elements and atomic types by atomic number and chemical and physical properties.



Metal

Elements are grouped into metals, semi-metals (including semiconductors) and non-metals. Metals are characterised by properties such as high electrical and thermal conductivity, malleability, high density and metallic lustre.

Metal categories

In the market, metals are usually divided into the main groups of iron, base metals, light metals and precious metals. An additional group is the alloying metals that are often added to iron (steel), including chromium, vanadium and manganese. Many other metals are produced in addition to these groups (often called 'minor metals').

Metallurgy

Processes for extracting pure metal from mineral-processed ore. These include pyrometallurgical (heat-based) and hydrometallurgical (liquid-based) processes.

Mine

Place where ores, coal or other geological resources are produced using excavation or solution techniques.

Mineral processing

Technologies used to increase the metal content of an ore through the production of concentrates or a reduction in impurities.

Minerals
Chemical compounds, alloys or pure elements with well-defined chemical compositions, crystal structures and properties, formed by geological processes.

Ore
An occurrence of metal-bearing minerals formed by geological processes that can be mined economically. If the mineral occurrence is not profitable to mine, it is not defined as an ore but can be considered as a potential resource.

Platinum-group metals (PGMs)
A group of six metals: platinum, palladium, rhodium, iridium, osmium and ruthenium. PGMs are used industrially in catalysts, electronics and the chemicals industry.

Precious metals
Gold, silver and platinum-group metals. Used, for example, in jewellery, electronics and catalysts, and as value hedging.

Pyrometallurgy
The melting and separation of metals using high temperatures (see also Electrometallurgy above).

Rare Earth Elements (REEs)
A collective name for the 15 lanthanides (atomic numbers 57 to 71). Scandium (21) and yttrium (39) are also often included. REEs are usually divided into two groups — light and heavy — based on their chemical behaviour. They are used in electronics and have special magnetic, optical and catalytic properties. Many REEs have very specific properties that make them difficult to replace.

Refining
Extraction of a pure metal from mineral-processed ore which, after having been treated in a smelter, can be refined to high-purity metal. In hydrometallurgical processes, the smelting step can often be omitted.

Shaft
A vertical or steeply inclined access into an underground mine.

Sintering
A process in which solid particles are fused together under high pressure and temperature.

Slag
Residual (usually waste) material or by-products formed during metal smelting.

Slag former
A material added to a melt of ore concentrates to remove unwanted substances from the pure metal.

Strategic raw materials/metals
Metals that are considered strategic from a forward-looking perspective, to achieve a priority function, such as the electrification of vehicles (electric cars). In the EU, this refers to raw materials that are particularly relevant for strategic technologies linked to the green transition, digitalisation and defence.

Tailings
Residual fine-grained waste materials produced during mineral processing. Stored in tailings dams.

Tailings dam
Earth-fill embankment dam for long-term tailings storage.

Waste rock
Mine waste in the form of barren, weakly mineralised or low-grade rock that is removed to access valuable ore. Usually separated continuously during operations, and deposed of in waste-rock dumps. Also known as ‘gangue’.

4. Background

»Sweden is one of Europe's most important mining countries with producing mines and great geological potential.«

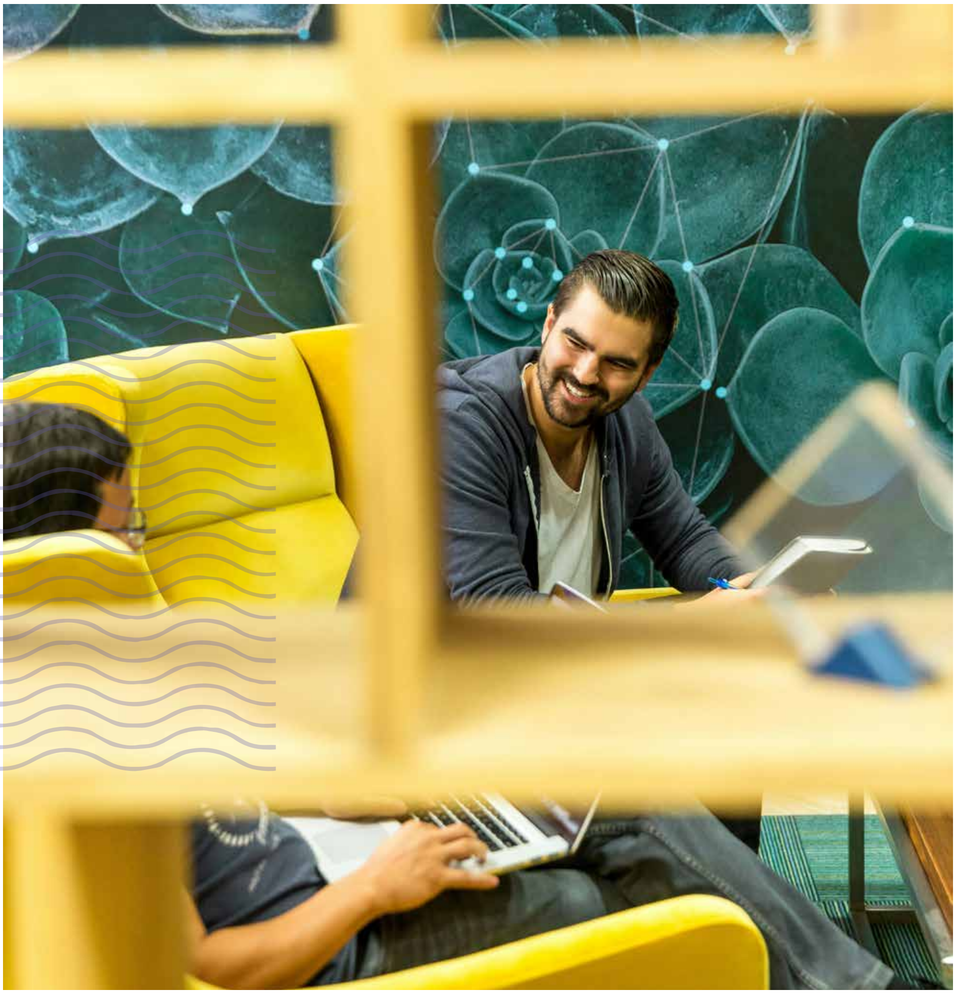
Reliable access to metals and minerals is needed in order to manage the transition to a fossil-free society. Demand will increase significantly as fossil fuels are phased out through increased electrification and digitalisation.

The transition requires not only larger volumes of traditionally used metals and minerals, but also substantially more of many of the metals and minerals that have so far been used only to a limited extent, such as lithium, indium, cobalt and graphite. Demand for metals and minerals will also increase as a result of population growth and improved living standards, as well as greater industrialisation in many parts of the world.

It will be a major challenge to secure a long-term sustainable supply of all the critical metals and minerals needed to enable the energy transition to occur. Producing these requires different technology and knowledge for exploration, extraction and production than for the base, precious and ferrous metals currently produced in Europe. The market for metals and minerals is global. Since the deposits mined today are often located in countries outside the EU, access to them also has a geopolitical dimension.

Sweden is one of Europe's most important mining countries and has, in addition to producing mines, great geological potential. Metals can also be recovered from products and mining waste. However, there are a number of barriers to the increased extraction and recycling of metals in Sweden and in the EU. There is a lack of knowledge regarding several of the critical metals, their occurrence and the extraction processes they need. In addition, large capital-intensive investment is required in new facilities.

Many metals occur together in mixed deposits, and depend on common or related processes at different stages of extraction. For this reason, the analysis in this report is not limited to individual 'strategic' or 'critical' metals and minerals, but utilises a broad perspective on the value chains from exploration to semi-finished products and components. The majority of the report’s observations apply to society's mineral supply in general.



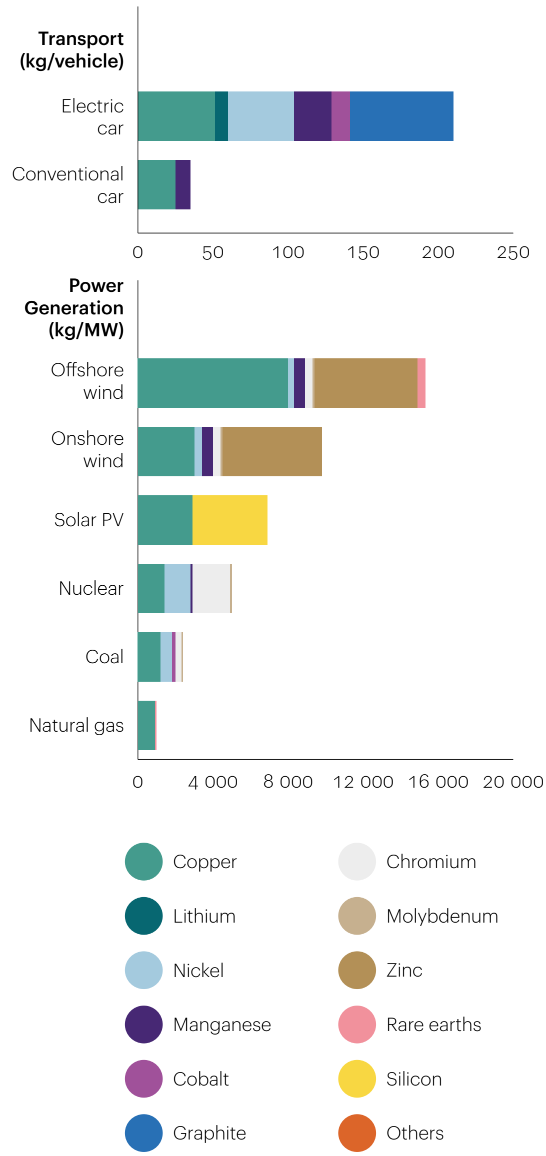
5. Why is the demand for metals and minerals increasing?

»Population growth, electrification and improved living standards will increase demand. However, the extent of this demand and which metals will be most critical are subject to a great deal of uncertainty.«

Several factors are driving the demand for metals and minerals: not only metals used in new technologies, but also steel (which requires iron and various alloying metals) and base metals such as zinc, copper, lead and nickel. Metals are not only needed in technologies for renewable electricity generation and batteries, but also in building materials, machinery and infrastructure. Economic growth, population growth and increased urbanisation also drive the demand for both traditional metals and critical and strategic materials such as rare earth elements (REEs). Metals are traded on a global market, so developments in other parts of the world have a major impact on Sweden and on Europe.

Strong drivers are increasing the demand for metals and minerals, but some factors are also dampening the increase rate. These include technological developments that lead to improved resource efficiency, alternative materials and solutions, and changes in consumer behaviour. Examples of this are the growth of a 'sharing economy' that reduces the demand for products, and the pace at which circular material and product flows can be established. The trend is not clear-cut, although it is now clear that it will take a long time for recycling to play a greater role in the supply of many metals and minerals.

Figure 2: Comparison between a conventional passenger car and an electric car, showing the difference in the number of metals and the amount of non-steel metals in kg/vehicle, as well as the content of different metals and minerals for different types of power. Source: The Role of Critical Minerals in Clean Energy Transition, IEA, March 2022.



Is it possible to quantify future demand?

The global demand for metals and minerals will grow significantly. For most base metals that are widely used today, demand will increase relatively in line with economic growth. For some metals, such as copper, demand will increase more rapidly. Demand will also grow strongly, albeit from low levels, for the critical/strategic metals that are being introduced and are required in line with developments in technology, electrification and digitalisation, and which are to some extent new to the market, (IEA, 2022).

Demand for the primary production of metals and minerals is therefore governed by technological developments,

TECHNOLOGIES REQUIRING CRITICAL METALS AND MINERALS

Wind turbines often include permanent magnets in their generators to provide a compact and energy-efficient solution. Neodymium permanent magnets provide the strongest magnetic field and give the greatest size and weight reduction. Ferrite magnets are much weaker and provide a larger and heavier solution. Electromagnets can also be used, but require additional technical equipment, resulting in a larger and more cumbersome design. Metals are also needed for turbine construction: aluminium, copper and steel, often alloyed with the critical metal niobium.

The development of **solar cells** is continuing rapidly. Conventional solar cells are based on silicon, while thin-film solar cells contain gallium and germanium, among other materials. Some high-efficiency solar cells also require indium or the semi-metal tellurium.

Electricity storage is a key issue in the move from a fossil fuel-based to a metal- and mineral-based society. **Battery technology** is developing rapidly but currently requires large amounts of metals and minerals, such as lithium, nickel, manganese and cobalt, as well as graphite and phosphorus. New batteries that provide higher performance and/or reduce the need for critical raw materials are under development; for example, lithium can be replaced by sodium in ion batteries. Another example is the move to solid electrolytes, which can increase battery performance and safety by eliminating flammable liquid electrolytes. Large-scale future storage may be done with so-called redox flow batteries, which require the critical metal vanadium.

Electric cars and other electric vehicles contain motors, batteries or fuel cells and electronics, all of which rely on a variety of metals.

The use of critical/strategic metals has allowed the development of high-performance technologies. These metals can be replaced to varying degrees by other metals that are more commonly available, but usually with reduced performance. However, technological developments have meant that the need for certain metals to achieve a specific level of performance can be reduced. For example, over the last ten years, cobalt has largely been replaced by nickel in lithium-ion batteries. Despite this, demand for cobalt has continued to grow because of the significant increase in demand for batteries.

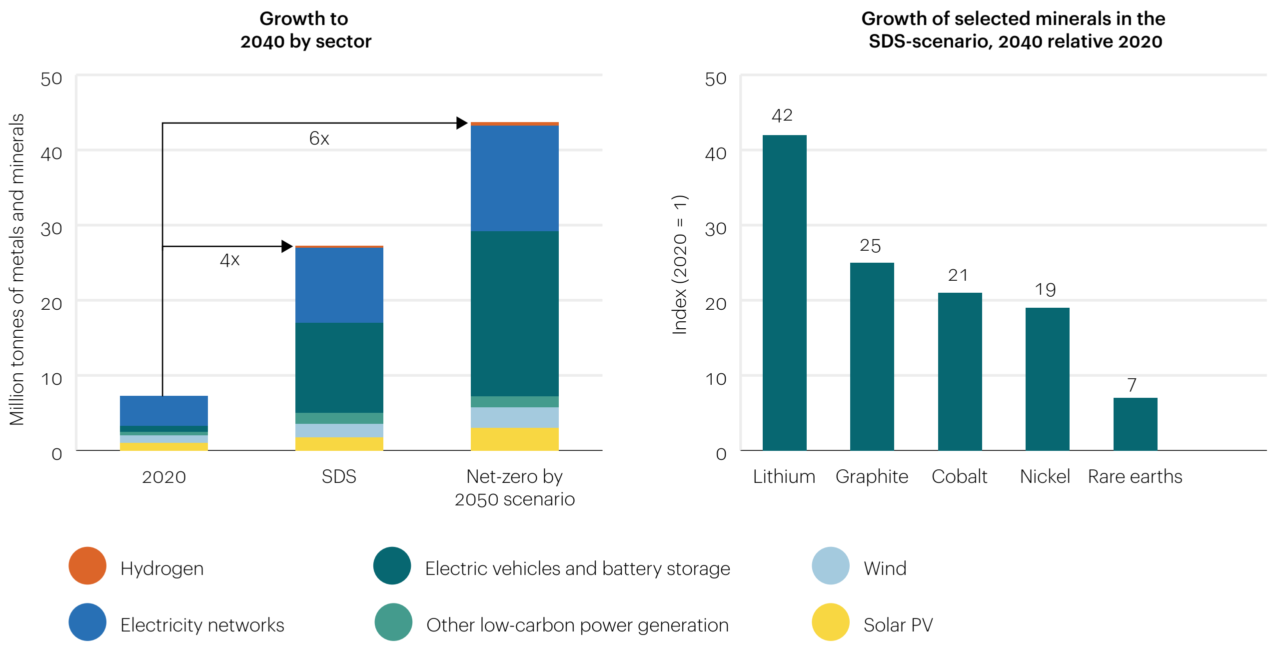
material-efficiency improvements and recycling. Some of these factors are dynamic in the sense that market pricing can handle shortage situations without significant consequences for society. As an example, the market share of lithium batteries containing cobalt has declined in recent years, partly due to a rise in the price of cobalt and partly because of more widespread knowledge of problems with the unsustainable extraction of the metal in the Democratic Republic of the Congo (Bobba, Mathieux, & Blengini, 2019).

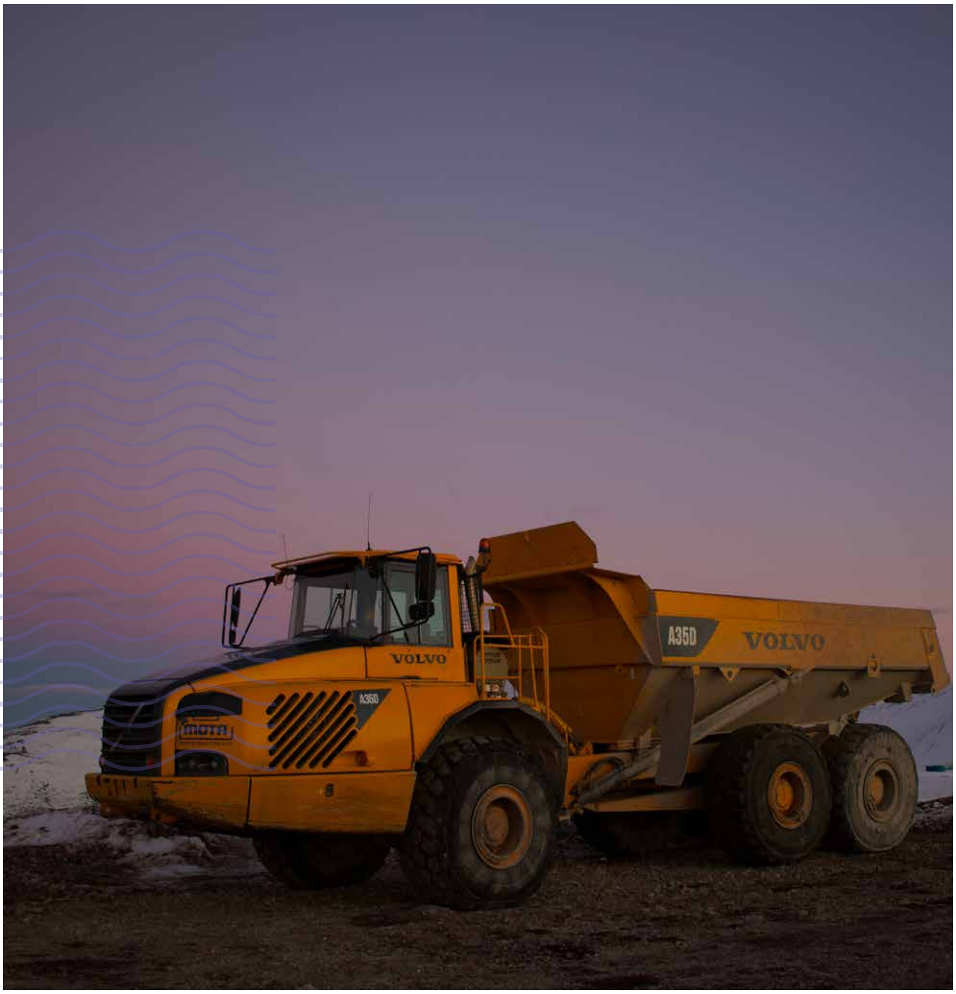
One challenge lies in lengthy project lead times that prevent the mining industry from keeping pace with the swiftly growing demand for many metals, particularly the rarer ones. This applies both to the production of metals that are typically by-products (such as antimony, indium, cobalt and bismuth) from the mining of other metals (such as zinc or copper) and those where the metal or a group of related metals is the main product (platinum-group metals or REEs, for example).

There are different sources and assessments of the future demand for metals and minerals. Several reports focus on the effect the transition of the energy system will have on demand, but do not consider population growth, increased living standards and technological developments. See Figure 3.

There is a consensus that demand for metals will increase. At the same time, the scale of this demand, and which metals will be most critical, are subject to a great deal of uncertainty. This depends, among other things, on the assessment of what alternative solutions or substitutes are available in different timeframes. Recycling will have very little impact in the short term, but its importance may increase in the longer term. Efficiency improvements may have a greater impact in the medium term.

Figure 3: Demand for metals and minerals could increase 4–6 times by 2040 due to the transition of the energy system from fossil fuels to electricity (SDS = Sustainable Development Scenario). Steel and aluminium are not included. Source: The Role of Critical Minerals in Clean Energy Transition, IEA, March 2022.

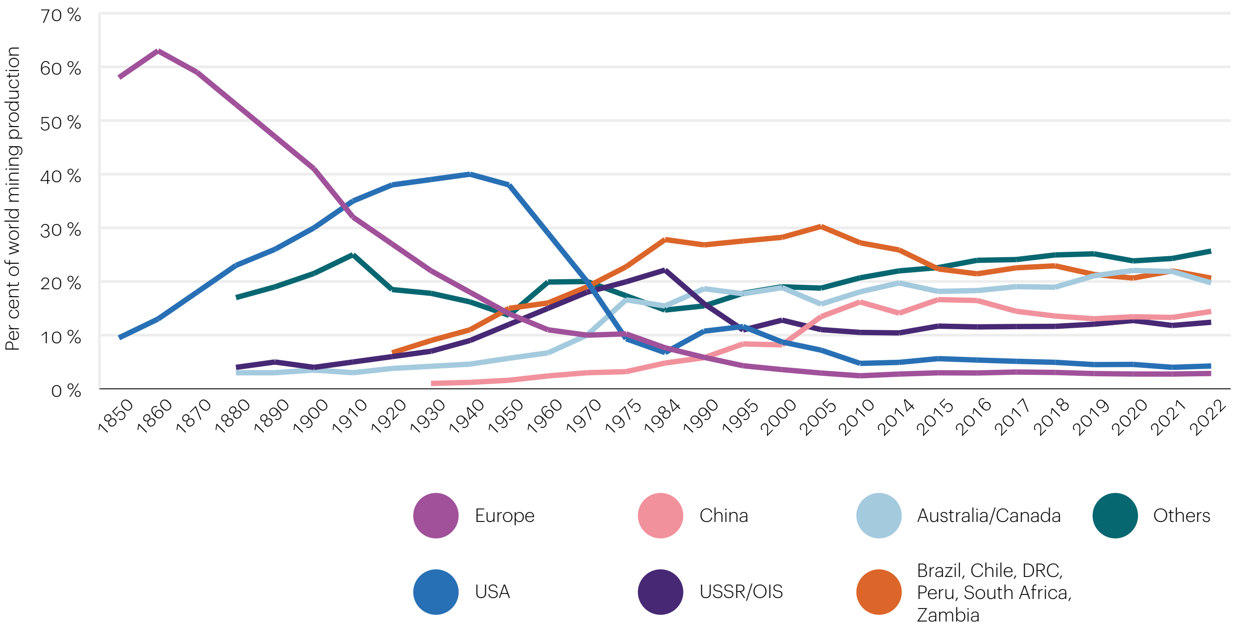




6. Europe's reduced mining role

»Europe possesses geological potential for critical metals and minerals, but there is a lack of metallurgical expertise, and big investment will be needed to extract them.«

Figure 4: The value of mining in different regions of the world over the period 1850–2022.
Source: RMG Consulting, 2023.



As shown in Figure 4, Europe was the dominant mining region long before the advent of industrialisation in the 19th Century, when its mining sector expanded to account for over 60% of the value of the world's mining production. At the beginning of the 20th Century, the USA rose to prominence, accounting for up to 40% in value terms, before mining took off in South America and in Africa, and then in Australia and Canada. The former Soviet states, led by Russia, were major mining countries until 1990 but have declined in importance in recent decades. China's mining industry has grown significantly since the mid-1990s. Today, mining is spread across large parts of the world.

Overall, Europe has lost much of its importance and currently accounts for only about 3–4% of the value of mining in the world, with countries in the southern hemisphere now contributing the greatest value share. Both Australia and Canada have strong mining industries. Developing countries are responsible for half the production of several strategic metals, and their share is increasing; about one-third of this production is controlled by companies domiciled in these countries (Ericsson, 2023).

Swedish mines are among the most efficient in the world (see Figure 5) and have low carbon footprint in a global perspective, which is illustrated in figure 6 (Copper) and figure 7 (Iron ore) . They compete on the global market and must therefore be efficient and innovative to be competitive. High levels of automation and efficient processes compensate for higher labour and input-material costs. In addition, Swedish

Figure 5: Swedish mines are among the most efficient in the world. Diagrams showing productivity relative to production in world zinc and copper mines. Source: Boliden, 2024.

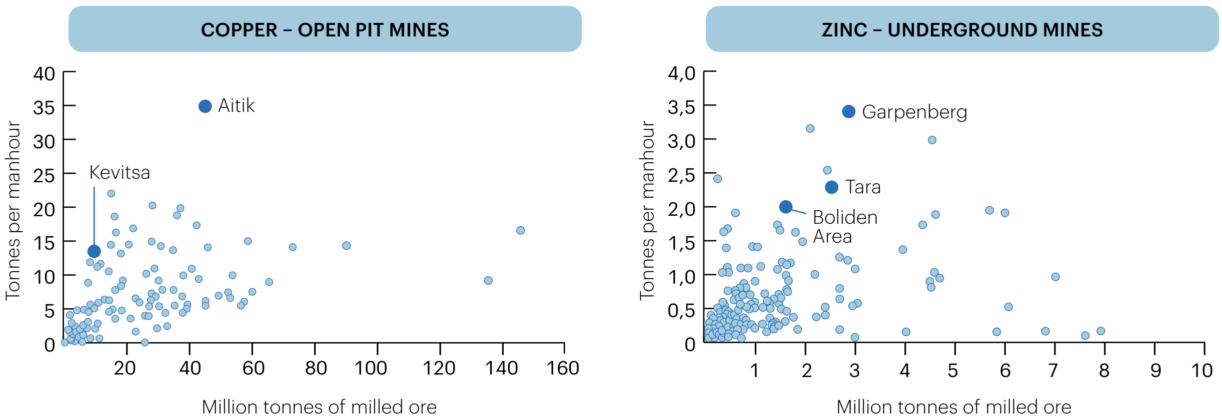


Figure 6: Green house gas intensity for global copper mines. The Swedish mines Garpenberg, Boliden and Aitik are among the best when it comes to carbon foot print. Source: Skarn Associates, 2024.

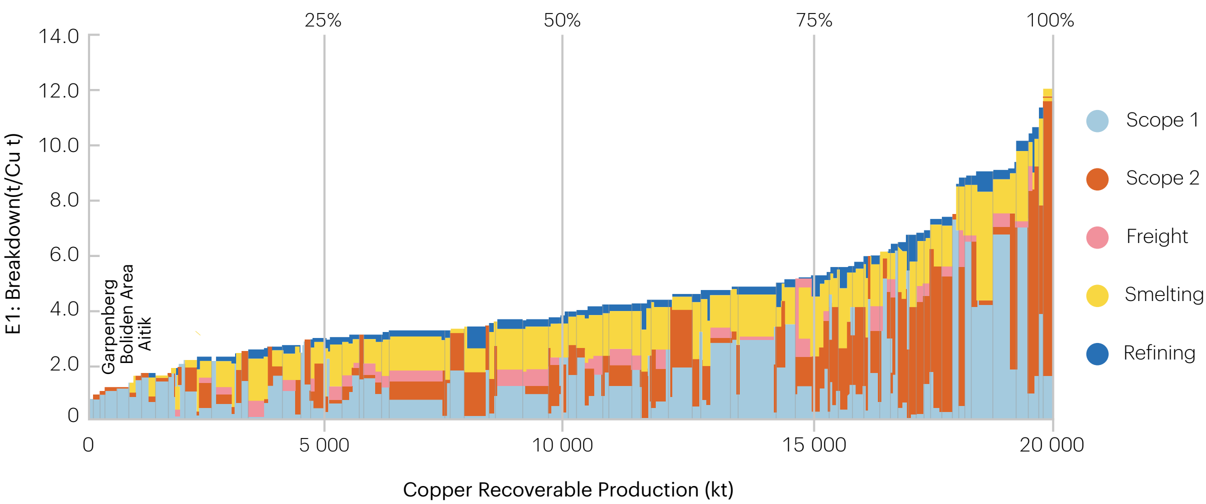
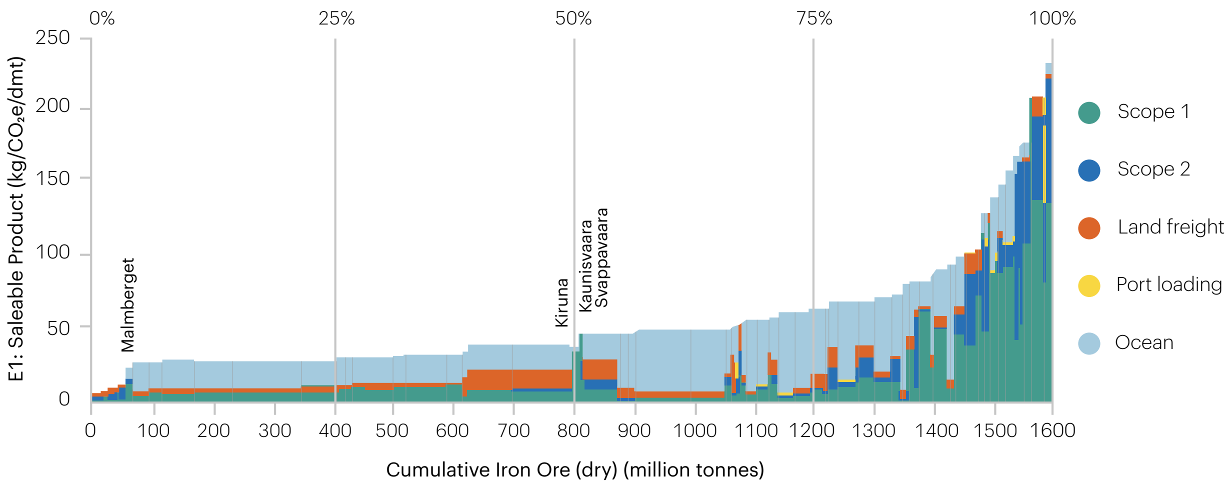


Figure 7: Green house gas intensity for iron ore mines. The Swedish mines Malmberget is among the lowest, but Kiruna, Kaunisvaara and Svappavaara have also low carbon foot print in a global perspektiv. Source: Skarn Associates, 2024.



mines often have a better work environment and a smaller local environmental footprint than those in many countries outside the EU.

The importance of the mining industry to national economies differs greatly from country to country. It is very important to those like the Democratic Republic of the Congo, Chile and Australia (Ericsson & Löf, 2019). In Sweden and Finland, meanwhile, the mining industry contributes more to the national, and especially the regional, economy than in other EU countries.

Lack of skills and technology for the new metals

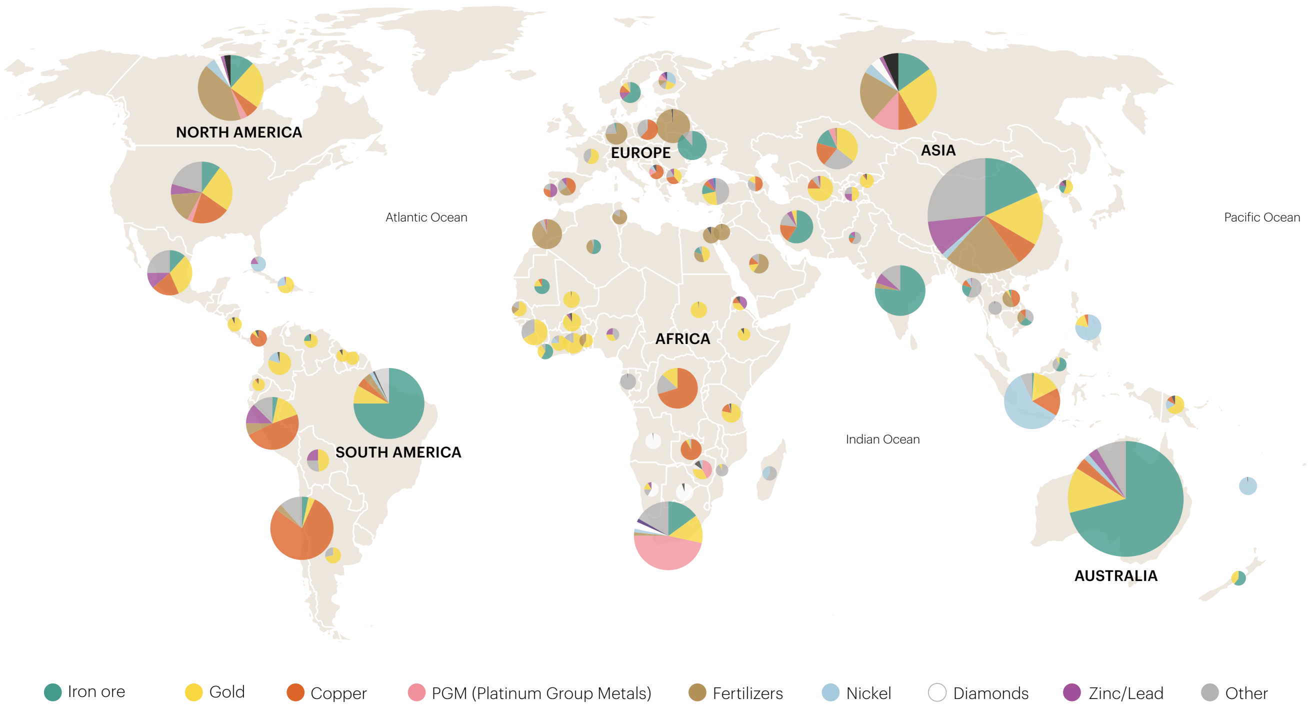
Europe possesses geological potential for a number of the critical metals that are essential for increased electrification and digitalisation. This potential could theoretically result in mining production, particularly in the Nordic countries (Jonsson, 2022). However, there is a lack of knowledge about these metals' geology, mineralogy and deposits, and the processes needed to extract and refine them. This is because industry has thus far focused on the metals and minerals that have traditionally been (and remain) locally important. For example, Sweden is strong in pyrometallurgy and smelting, but the new metals require completely different processes, infrastructure and skills such as hydrometallurgy, electrochemistry and chemical separation (see also Chapter "Sweden as a mining country").

Today, virtually no new facilities are being constructed in Europe because of the high investment costs needed in new technology and expertise, as well as high energy prices. Instead, the focus is on expanding and developing existing facilities based on conventional technology for extracting base and ferrous metals. The new facilities required would demand substantial investment that a single company would find challenging to secure. Achieving this necessitates coordinated investment and technological development within the EU.

7. Geopolitical aspects of the market for metals and minerals

»Sweden can learn from Canada and Australia. Their mining industries operate under similar conditions and challenges, but have different strategies for their role in the market.«

Figure 8: Mining in a global perspective. The size of the circles represents the value, and the colours indicate the metals involved. As shown, the southern hemisphere is now dominant in mining, while Europe's contribution is modest. Source: RMG Consulting, 2023.



Value chains for metals and minerals are global. The various stages in the supply chains, from extraction to finished product, are not always located in the same country, and there is global trade even in mineral concentrates. The transition to climate-friendly energy systems, electrification and digitalisation affects the demand for specific minerals. This shift results in a transfer of power from oil-producing nations to countries with access to metals and minerals, or to refining processes.

The market concentration involving the countries that extract critical minerals is greater than that for oil and natural gas, as shown in Figure 9. For example, the three largest producer countries of lithium, cobalt and REEs account for more than three-quarters of global production. In some cases, a single country can contribute more than half the world's production. Examples are the Democratic Republic of the Congo, which accounted for 70% of global cobalt production in 2019, and China, which represented 60% of global REE output that year (IEA, 2022). However, corporate concentration of cobalt production is significantly lower than country concentration, as illustrated in Figure 10 (Ericsson M., Löf, Löf, & Müller, 2023).

This concentration becomes even more significant when considering subsequent refining stages. China dominates the refining of REEs (90%) and also holds a strong position in nickel, lithium, cobalt, graphite and manganese refining. However, in all these cases, production relies heavily on imported ores and concentrates. China also influences extraction in other countries through full or partial ownership of crucial companies and mining projects. For instance, the Chinese lithium company Tianqi Lithium has a majority

Figure 9: The market concentration for metals and minerals used in the energy transition is greater than that for traditional fuels such as oil and gas. Source: IEA, 2022.

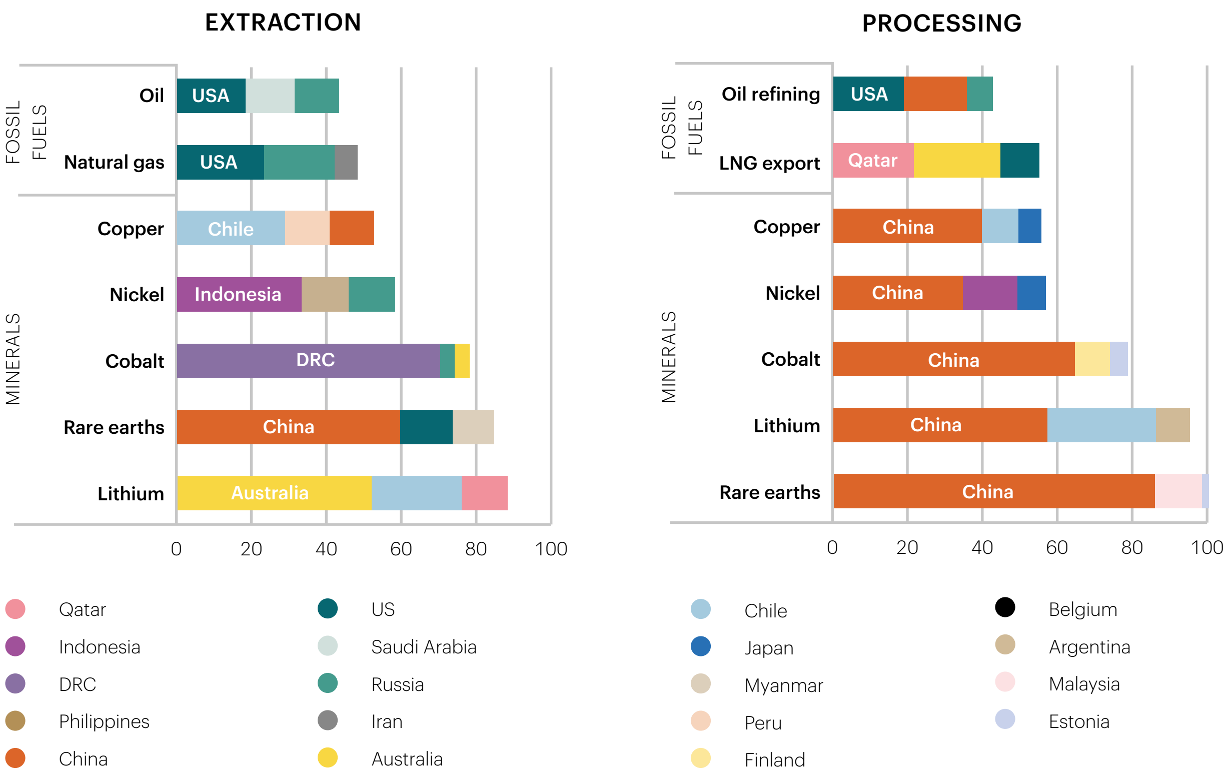
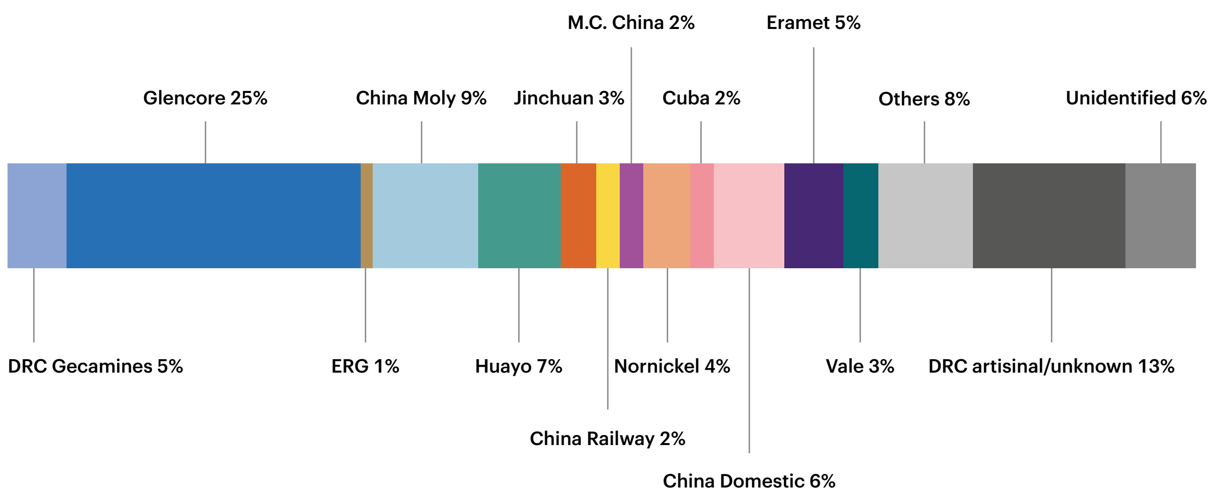


Figure 10: Company control over cobalt mining, 2018. Source: RMG Consulting.



holding in the world's largest lithium mine, Greenbushes in Australia, and a significant portion of Chile's largest lithium producer, SQM (IEA, 2022).

The demand for critical metals is already leading to geopolitical conflicts and rivalry among the great powers. China produces most of the germanium and virtually all of the gallium used worldwide today. A notable example of geopolitics impacting value chains was China's decision in the summer of 2023 to restrict the export of gallium and germanium, two metals crucial for manufacturing the most advanced computer chips. Among other areas of application, these chips are used in training AI models like ChatGPT (European Commission, 2023).

Although market concentration is significant, it is debatable how much power countries controlling new value chains can gain, and what ability they have to exercise this power (Gholz & Hughes, 2021). It is often emphasised that there are greater possibilities for substitutes for metals than for fossil energy. The harm caused by a supply shortfall of metals is lower, since any absence would primarily affect the development of new technologies while existing technical solutions could continue to be used in society.

When supply is limited, the increased demand for minerals contributes to intensified competition which, in turn, can lead to rivalry among importing countries. Strategies to secure one's supply, such as investments in countries with abundant resources, may be perceived as interventions that block other states' access and disrupt market mechanisms. Chinese investments in Africa is one such example. Technological development and the need for certain metals are also closely intertwined with developments in security policy.

In addition to states attempting to influence supply chains, geopolitics is also associated with several other risks that can cause supply disruption. These include:

- Resource nationalism and export restrictions in producer countries;
- Instability in a producer country affecting exports; and
- Natural disasters affecting exports.

(IRENA, 2023)

RESOURCE NATIONALISM

Resource nationalism refers to the practice where producing countries attempt to retain a larger share of the added value in their country. Export restrictions on minerals are common and may include fees and quota systems, for example (OECD, 2023).

However, the extent to which producer countries are favoured is questionable, as in many cases, they do not have the necessary skills and infrastructure for other input materials for further processing. This leads to a lack of investment in smelters and a consequent loss of revenue (Fliess, Idsardi, & Rossouw, 2017).

However, there are examples where export restrictions are likely to have helped establish domestic industries, such as China's processing of REEs and Indonesia's nickel-smelting and refining industry.
In recent years, partnerships have been established between some countries to make both parties feel they are benefiting; for example, the Chinese battery manufacturer CATL is investing in the extraction and processing of lithium in Bolivia.

INSTABILITY AND NATURAL DISASTERS

Instability and natural disasters are external events that can limit opportunities to extract and export minerals. Most of the raw materials perceived as critical are primarily produced in countries that are unstable and/or vulnerable to climate change (Owen, 2022). There are also cases where various interests have conflicting claims to the land where minerals are extracted, which can also affect the possibilities of establishing and operating mining activities.

The EU's Critical Raw Materials Act (CRMA), outlines several strategies that include increased domestic self-sufficiency and partnerships with other countries, as well as stockpiling and recycling. The design and implementation of these strategies requires a balance against other societal goals.

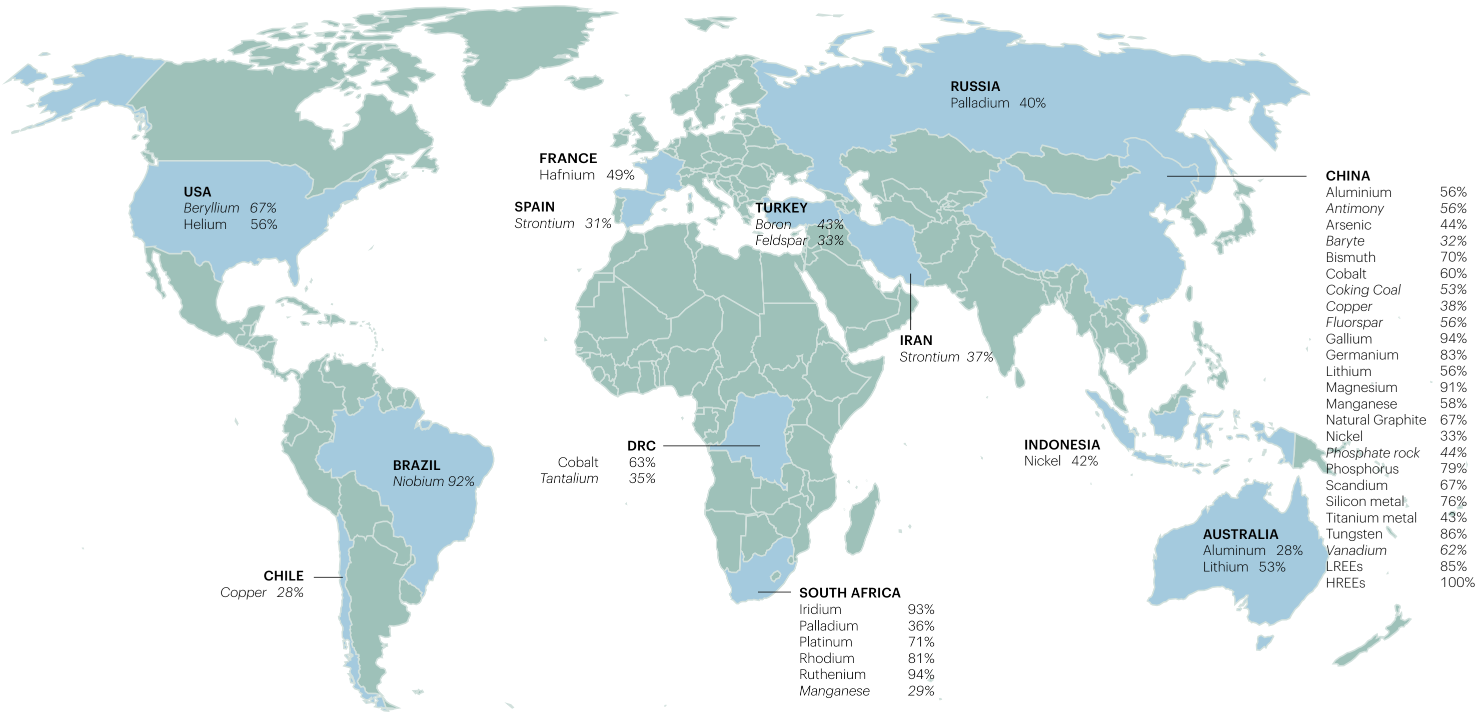


Figure 11: The world's main suppliers of critical materials with their market share in per cent for mining (plain text) and refining/processing (italics). Source: EU Commission Joint Research Centre, 2023.

For instance, the EU has a goal of regional autonomy, meaning the ability to act independently from other regions. This is sometimes interpreted as 'self-sufficiency' and 'independence', which can conflict with the objectives of free trade and mutual dependencies for conflict prevention.

The value chains of metals are often more complex than those of oil

Strategic metals and minerals are often compared to oil from a geopolitical perspective. However, the situation is both different and more complex for metals and minerals. Part of the explanation lies in the underlying processes that have shaped the formation of mineral deposits.

Oil has an essentially singular formation process during a very limited time-frame in geological history. Minerals, on the other hand, have formed throughout most of Earth's history, from 4 billion years ago to the present day, in many active geological settings. Since they can form through a wide variety of processes in different geological environments, ore-forming systems are also extremely diverse. Coupled with the fact that ores are diversified, this makes them more challenging to locate compared to oil and gas.

An additional complication is the absence of transparent global market prices for most of the critical raw materials. For oil and gas, there are functional markets where supply and demand dictate the price. Such markets also exist for the majority of traditional metals.

For most of the critical metals, however, the situation is different: their pricing is negotiated directly between buyer and seller without transparency from external parties. Prices for various critical metals are also relatively inelastic. Increased demand may lead to a higher price, but seldom to increased production. This is partly due to the fact that opening a new mine can take at least 10–15 years, and partly because some of the critical metals are by-products of another primary metal. In the latter case, it is mainly the price of the base metal that dictates the extraction of the by-product metals. See also chapter "Definition of critical raw materials and their complex market" and the glossary.

Some critical metals, such as REEs, have a relatively small global market in terms of both volume and value. This means that they can suffer a price collapse if global production increases rapidly with the opening of just a few new larger mines, despite their criticality. It also makes large mining companies less willing to invest in such projects.

Simply having a producing mine is not enough to ensure access to metals and minerals. It is also necessary to have access to the various smelting and refining processes that are needed to produce pure metal and, by extension, critical semi-finished products such as batteries or magnets. The reason for this is that these process industries are highly capital-intensive and require specific expertise.

The green transition is leading to increased dependence on various critical raw materials and the value chains where they are processed. This could have an impact on geopolitics, making it more about exerting influence over not only the early stages of the value chain, but processing as well (Emanuel Hache, 2018).

China's dominant position

From a global perspective, China dominates the processing steps for the production of several critical metals and minerals. It also dominates the entire supply chain for REEs, in terms of both primary extraction and refining into pure metals and semi-finished products. The chart in Figure 12 shows how Chinese companies' control over the production of cobalt, lithium and REEs increased significantly between 1985 and 2018, compared to that of companies from other regions.

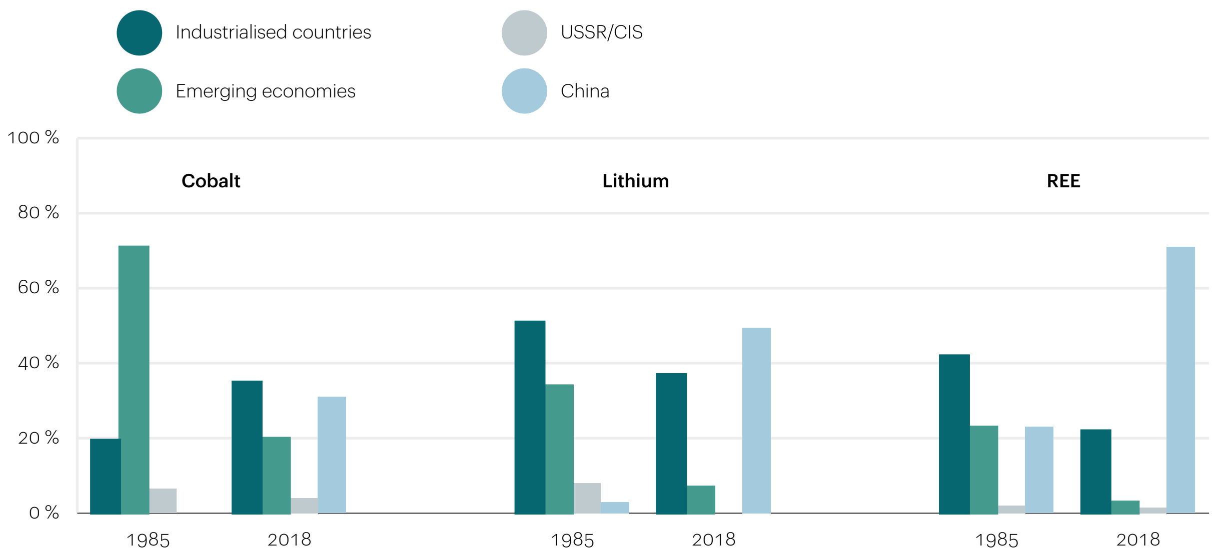
China and Australia are the world's two largest, roughly equal, mining countries ranked by value of production, excluding coal, oil and gas. China accounts for about half of the world's total use of most metals and minerals. However, China has to import large quantities of base metals such as copper, as well as iron ore and bauxite, in total volumes and values that far exceed those of strategic metals. Chinese iron-ore imports alone in 2022 amounted to 1,100 million tonnes, representing 70% of the world's total imports. The country's imports of copper and nickel are also significant.

In an international comparison, China's mining industry consists mainly of relatively small mines and mining companies. This is for historical and geological reasons. Until the revolution in 1949, China was primarily an agricultural country. The mining industry consisted mainly of small-scale mines with manual operations, primarily extracting coal. With rapid economic development, a mechanised mining industry emerged, but the sector is still divided into many small entities. Geological reasons also contribute to this situation. Many Chinese mines extract ores and ore types that are seldom found in larger volumes, resembling early mining practices in, for example, Central Europe.

The average Chinese iron-ore mine produces around 100,000 tonnes per year. Although there are perhaps 3,000 mines in the country covering a wide size-range, none is truly large. For comparison, annual production from Kiruna and Malmberget in Sweden is in the order of 10–15 million tonnes each, while Kaunis, considered a small mine on a global scale, outputs around 2 million tonnes. There is no Chinese company among the world's top ten, even when considering companies' production outside China.

China's expansion through the acquisition of mines worldwide, particularly in Africa, has garnered significant attention. However, despite an aggressive strategy, Chinese mining companies outside China only control around 3% of the total value of global mining production. The top ten non-Chinese companies collectively control significantly more – between 25 and 30%. Hence China's influence over the global mining industry should not be overstated. However, even though the pace of overseas expansion appears to have slowed in the last five years, influence is likely to increase as China is expected to continue its efforts to reduce import dependence (Ericsson, Löf, & Löf, 2020).

Figure 12: China's control over critical metals resources has increased over the past 30 years. Its percentage share of global production of cobalt, lithium and REEs. Source: RMG Consulting, Presentation at the conference: Mineral deposits as a basis for raw materials safety, Kraków, 10 May 2022.



China's dominance over critical metals is not a 'given'. In 2010, China reduced exports of REEs to Japan following a border dispute between the two countries. Japan and most other countries interpreted this as China using export restrictions as a tool to influence Japan. China itself claims that it regulates exports of REEs in order to promote domestic industry and reduce environmental impacts. When the restrictions were introduced, prices rose sharply but subsequently receded again. A decade later, China's share of global REE output had fallen because extraction had increased in other countries. Japan also launched several strategies to reduce its vulnerability, such as material-efficiency improvements and the development of technologies not using REEs. Japan also stocks some critical materials to secure the needs of its high-tech industry in case of temporary import restrictions. In 2023, China imposed export restrictions on gallium and germanium, and on separation technologies for REEs.

China's dominant role in critical raw materials is multi-faceted. As shown in Figure 13, the country holds a dominant position in the processing of many metals and minerals. However, this cannot be directly translated into China's ability to leverage it as an effective negotiating tool. Even in the case of Japan, where the country had significant vulnerability, it is doubtful whether China gained anything in the short term by restricting exports. In the long run, it lost its dominant position in the extraction stage.

New legislation and governmental support in other countries

Legislation and governmental support for national value chains of critical raw materials outside the EU, such as the Inflation Reduction Act (IRA) in the USA, are generally considered to have little impact on Europe's macro economy. However, it has already become clear that other regions can attract significant investments from EU-based companies that were originally intended for Europe (Automotive News Europe, 2023) (Electrek, 2023) (CNBC, 2023).

The following is a selection of the most important new legislation and governmental action that has had significant impact on the mining and critical mineral industries worldwide over the past 2–3 years. In addition to these, there is China's continuing focus on supporting and strengthening its domestic raw-material industries, and on ensuring access to critical raw materials from other countries.

USA: Inflation Reduction Act (IRA)

Signed in August 2022, the IRA is the largest measure ever taken by Congress and the US government to combat climate change. It provides billions of dollars in tax incentives for renewable energy, and aims to increase domestic access to minerals to support the transition to renewable energy, electric vehicles and batteries.

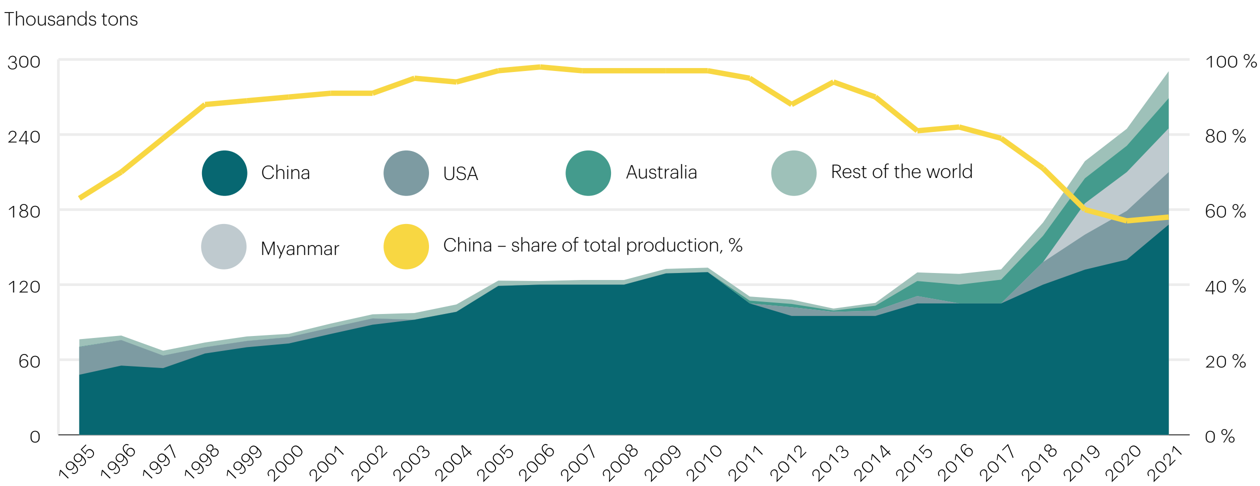
The IRA incentivises domestic mineral production through tax credits for fossil-free vehicles and deductions for advanced manufacturing processes. The law allocates up to US$500 million for 'enhanced use' of the Defence Production Act (DPA) to strengthen the USA's supply chain for critical minerals. Despite these provisions, the progress towards the use of domestic sources for critical minerals is challenged by both the well-established Asian supply chain, and the fact that developing new mines in the USA takes a considerable amount of time.

EU: Critical Raw Materials Act (CRMA)

Announced in March 2023, the CRMA aims to promote industrial sustainability, the EU's strategic independence, and resilience in the EU's value chains. The goal is to ensure a secure and sustainable supply of raw materials crucial to the EU's industry, and to reduce significantly the EU's dependence on imports from suppliers in individual countries outside the union.

The CRMA established a list of strategic raw materials crucial for technologies related to the green transition, digitalisation and defence. The regulation also sets benchmarks for domestic capacity in various parts of the strategic raw-materials supply chain to be achieved by 2030. For the strategic raw materials consumed within the EU, the objective is that 10% should be extracted, and 40% processed, within

Figure 13: China's share in the extraction and production of REEs declined following a border dispute with Japan in 2010 that had global consequences. Source: Rizos & Righetti, 2022.



the union. Additionally, the goal is for the EU's recycling capacity to cover 25% of consumption, and for a maximum of 65% of each strategic raw material to be imported from a single country. The proposal includes measures such as national programmes for basic geological mapping, and the possibility of applying to become a so-called 'strategic project' with time-limited permitting processes. A linguistic and legal review of the proposal is set to come into effect in 2024.

Australia: Governmental support and funding for critical minerals

Alongside China, Australia is one of the world's most significant mining countries. It is the only industrialised country among the top ten nations where the mining industry is the largest industry sector, thus being crucial for the country's economic development. Exploration is thriving in the country, thus ensuring substantial ongoing mining production.

Many Australian 'junior' companies[1] are also active worldwide, particularly in Southeast Asia, Africa and Latin America. At both the state and federal levels, Australian politicians see the upcoming increase in demand for metals and minerals as an opportunity to supply many of the raw materials required. In addition, they see the opportunity to continue the country's economic development based on both mining production and increased processing. Significant programmes have been initiated to acquire additional geological knowledge to enhance understanding of the industry's opportunities and challenges.

In October 2023, the Australian government announced an increase in the state budget by A$2 billion for financing the production of critical minerals. With this, the government's investment in Australian resources increased to A$6 billion, which is expected to solidify Australia's position as a global leader in the supply of critical minerals. The funding will double the capacity of Australia's Critical Minerals Facility to finance Australian mining and processing projects for critical minerals.

Canada: Federal Strategy for Critical Minerals and Intervention against Chinese Ownership in Critical Lithium Projects

Like Australia, Canada has significantly increased its mining production since the 1960s. While the mining industry is not as dominant as in Australia, the country is still one of the world's leading mineral producers. The stock exchanges in Toronto and Vancouver serve as global financial centres for small and medium-sized mining companies. Canadian junior companies are active primarily in Latin America but also in other parts of the world, such as Africa. Like Australia, the mining industry in Canada is regulated at the provincial level, with several provinces having modern legislation that is considered attractive to investors.

In December 2022, the federal government released the Canadian Critical Minerals Strategy. Among other things, this calls for accelerating regulatory decisions for mining projects.

After the introduction of stricter regulations on foreign investment in the critical minerals sector, in November 2022 the Canadian government ordered four Chinese companies to divest their assets in lithium companies in the country. The affected companies were Sinomine (Hong Kong), Rare Metals Resources, Chengze Lithium International and Zangge Mining Investment (Chengdu), all of which were required to divest their investments in Power Metals, Lithium Chile and Ultra Lithium respectively – three junior companies prospecting for lithium deposits in Canada.

1 Junior companies usually have no income from mines of their own, but conduct exploration with the help of venture capital.

The decision was made under the Investment Canada Act (ICA), which examines foreign investments from a national security perspective. The action was part of a broader strategy by the Canadian government to limit the involvement of foreign state-owned companies in the industry. However, the decision has raised concerns. Robert Friedland, the founder of Ivanhoe Mines Ltd., one of Canada's largest mining companies, stated that Canada's crackdown on Chinese investments in critical minerals would make it more challenging for the Canadian mining industry to produce the metals needed for the global energy transition by – in the long run – stifling a crucial source of venture capital for junior companies.

New partnerships with mineral-rich countries are needed to secure the supply of metals and minerals

Europe can no longer rely on functioning global trade to meet its needs. To reduce the vulnerability of supply chains, Sweden and the EU should enter into new strategic partnerships with countries that have either mineral resources, refining processes, or the production of strategic components.

Sweden is already a major exporter of metals and minerals within the EU but can still learn a lot from Canada and Australia as mining countries. Their conditions and challenges resemble Sweden's, but they have different strategies for securing their supply of critical metals and minerals, and their role in the market.

Africa has significant resources of metals and minerals. African initiatives, such as the planned economic zone for battery raw materials and components (a collaboration between Zambia, the Democratic Republic of the Congo and the African Union) deserve Swedish and European support. Sweden and Europe should expand cooperation with African countries for several reasons: to secure access to critical metals and minerals; to strengthen the economies of those countries; and to contribute to more sustainable mining globally.

8. Sweden as a mining country

»Sweden's industrial development is based on its natural resources, engineering, research and successful entrepreneurship.«

With a long and rich history of mining, Sweden is one of the largest, most important mining countries in Europe today, in terms of both production and technology. In particular, the long tradition of continuously developing technology and science around mines and ore prospecting has led to a strong and innovative Swedish industry, often referred to as 'the Swedish mining cluster', see below.

Swedish mines produce iron ore, base metals (copper, lead and zinc) and precious metals (gold and silver). Sweden is also one of the world's largest producers of high-grade iron ore, as well as accounting for 92% of the EU's iron-ore production (SGU, 2023). Figure 15 shows Sweden's share of the EU27's production of copper, lead, zinc, iron ore, gold and silver.

Sweden's mineral-rich bedrock also contains several metals for which demand is increasing. In some cases, they are found in the same orebodies as metals already being mined, which results in them ending up in mining waste or being sold raw to be extracted in another country. They can also occur in other deposits in areas where there are no active mines at the moment.

The map in Figure 17 shows examples of areas with potential for new discoveries of critical metals and minerals. Knowledge of the content in Sweden's bedrock is limited since the focus has so far been mainly on iron ore and base metals, and the country's exploration tools are adapted to these deposits.

Figure 14: Sweden's mines and mineral occurrences in 2022. Source: Statistics of the Swedish Mining Industry 2022, SGU 2023:1.

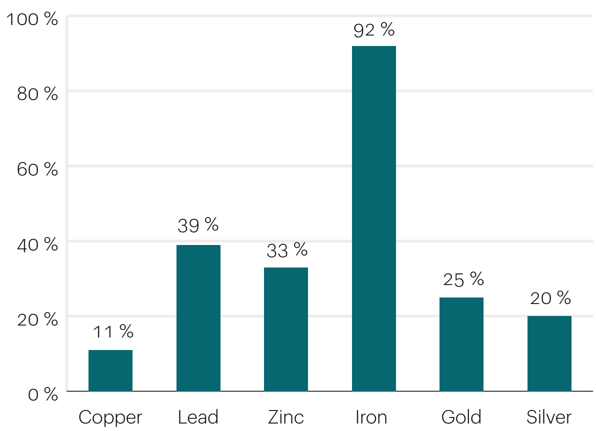
ACTIVE MINE

- Iron Oxide
- Sulphide
- Precious Metal

TYPE OF MINERALISATION

- Iron Oxide
- Oxide
- Sulphide
- Precious metal

Figur 15: Sweden's share of the EU27's production of copper, lead, zinc, iron, gold and silver. Source: Statistics of the Swedish Mining Industry 2022, SGU 2023:1.



Along with base-metal ores such as copper, lead and zinc, as well as a lesser production of precious metals (gold and silver), iron ores have traditionally been the most significant target for the Swedish mining industry. They are still the focus for both exploration and production. However, with the start of mining at Boliden's Kankberg gold-tellurium mine, Sweden has become an important international producer of the semi-metal tellurium, crucial for high-efficiency solar cells. The EU's only graphite mine, at Voxna in Hälsingland, operated for a few years up to 2016, while a new graphite mine is being planned at Vittangi.

The Swedish mining 'cluster'

Sweden's industrial development is based on its natural resources, engineering, research and successful entrepreneurship. Swedish primary industries process the country's forest and mineral resources with the help of an almost fossil-free electricity system where hydropower plays a crucial role in ensuring well-functioning electricity supplies. These industries are world leaders and are globally competitive thanks to their high level of technology. The companies involved are professional buyers of equipment from Sweden's engineering sector, challenging it to be a market leader as well, and hence more competitive globally. This symbiosis forms the basis for the Swedish mining 'cluster'.

The cluster consists of the mining sector, suppliers of mining equipment, industries that produce input goods for the mining industry, consultants and research and development resources at universities and companies. Downstream in the value chain are the steel and metal industries that process materials produced by the mining sector. The Swedish mining cluster accounts for 3% of the country's GDP, 8% of Sweden's exports and an estimated 100,000 to 125,000 jobs each year. On a provincial basis, it is the most important contributor to the provincial economies of Norrbotten and Västerbotten (Copenhagen Economics, 2021).

The Swedish mining equipment industry consists of a large ecosystem of highly specialised companies such as ABB, Epiroc, Sandvik, Volvo, Scania and SSAB: all of them world-leaders in their respective fields. The interdependence between the mines and these equipment manufacturers has been, and remains, very important. New high-tech companies are emerging that will contribute to the continued successful development of the mining cluster, such as Minalyze, Oryx Simulations, Mobilaris and OreExplore. Companies like Northvolt contribute indirectly by increasing the demand for battery metals and hence also the development of new technologies for their extraction and recycling. See Figure 22.

Exploration in Sweden

Like mining, prospecting and exploration for ores and minerals has ancient origins. Until the 19th Century, most ore discoveries were based on finding ore in rock outcrops. The subsequent development of increasingly sophisticated methods, combining geology, geophysics, geochemistry and rock drilling technologies, has led to the discovery of deeper, concealed deposits – deposits that were previously inaccessible.

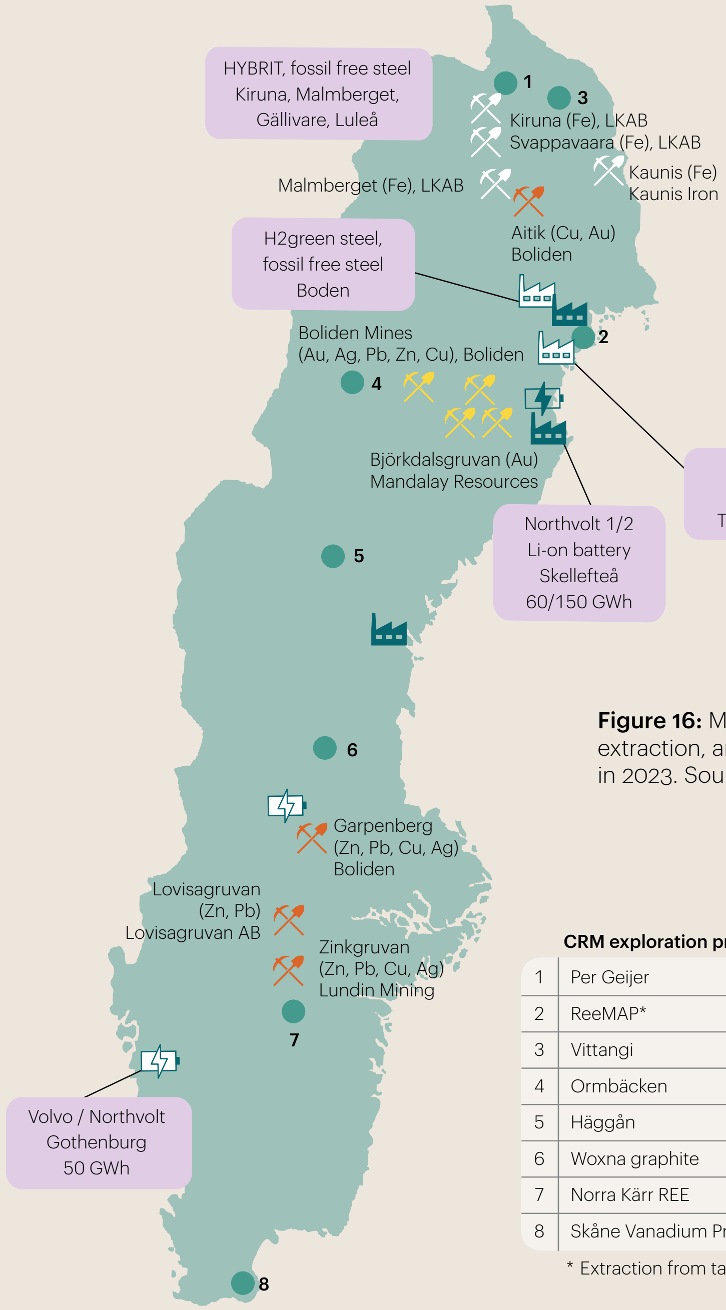


Figure 16: Mines, metal and mineral extraction, and battery projects in Sweden in 2023. Source: RMG Consulting, 2023.

CRM exploration projects in Sweden (selected)

1	Per Geijer	LKAB	REE, P
2	ReeMAP*	LKAB	REE, P
3	Vittangi	Talga Resources	Graphite
4	Ormbäcken	Eurobattery Minerals	V, REE, Mo
5	Häggån	Aura Energy	V, Ni, Mo
6	Woxna graphite	Leading Edge Materials	Graphite
7	Norra Kärr REE	Leading Edge Materials	REE
8	Skåne Vanadium Project	Province Resources	V

* Extraction from tailings.

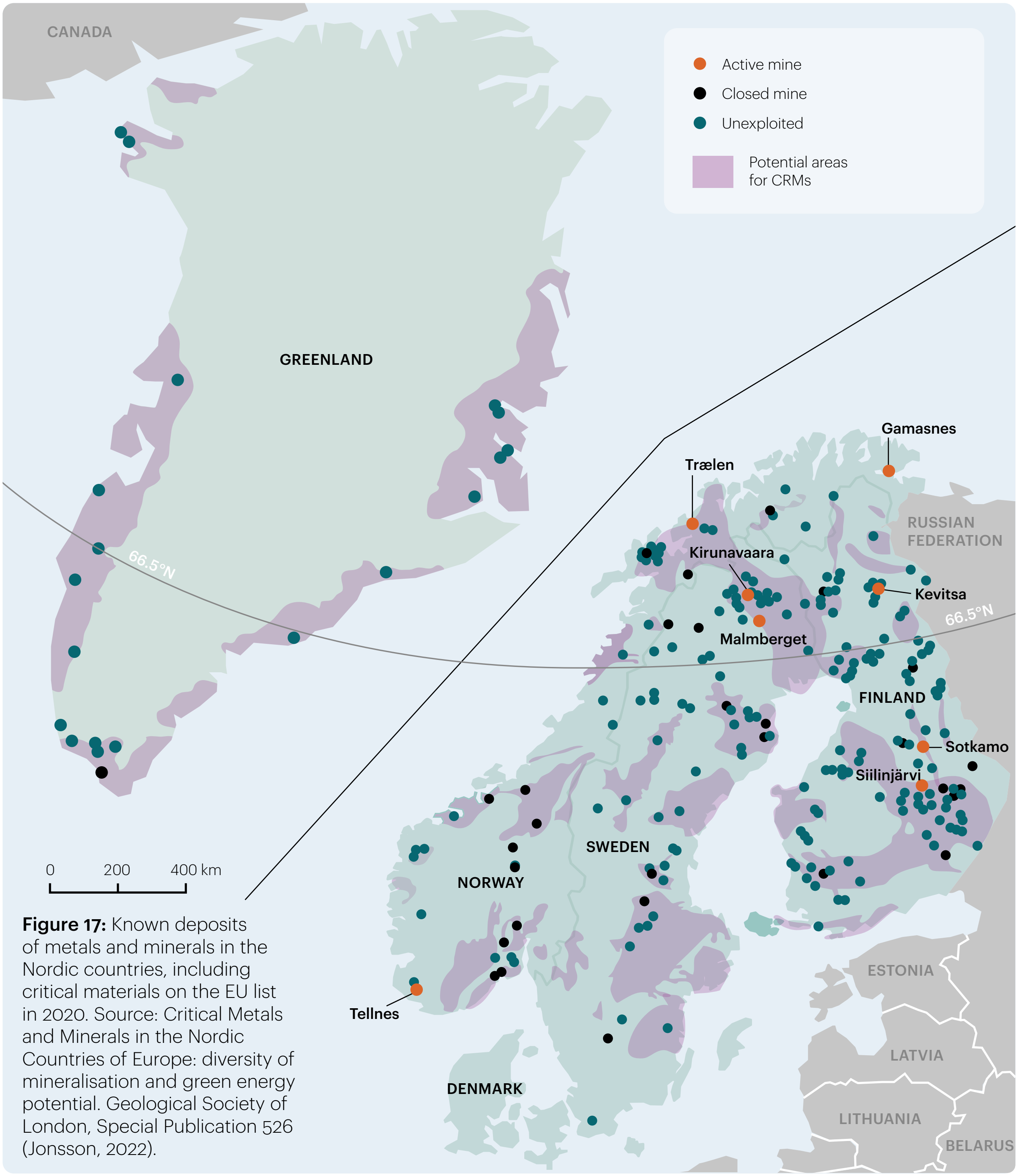


Figure 17: Known deposits of metals and minerals in the Nordic countries, including critical materials on the EU list in 2020. Source: Critical Metals and Minerals in the Nordic Countries of Europe: diversity of mineralisation and green energy potential. Geological Society of London, Special Publication 526 (Jonsson, 2022).

Carried out by a few large Swedish companies as well as smaller ones (both Swedish and foreign), exploration has mainly focused on traditional base, ferrous and precious metals. With greater awareness that society needs other, often critical, metals and minerals, exploration for these has also intensified recently. Within Sweden, exploration and mining projects are now focusing on commodities including REEs, graphite, fluorite, phosphorus, vanadium and lithium.

The big Swedish mining companies, LKAB and Boliden, together account for 78% of exploration investment, while almost 85% of the exploration is being carried out by companies that are operating active mines in Sweden (SGU, 2023). Most of these companies' expenditure consists of so-called near-mine exploration; that is, within or near existing mining operations. The remainder is carried out by junior companies, which usually have no revenue from mines of their own but are financed by venture capital. Meanwhile, Sweden is also attracting interest as a target for exploration from the largest global mining giants. New exploration players are important for the inflow of new ideas, technologies and approaches to Swedish exploration.

Despite the need for critical and strategic metals and minerals, most exploration investment is targeted on metals such as copper and gold. This is true not only in Sweden but also globally (S&P, 2023). At the end of 2022, no fewer than 640 exploration licences were valid, covering 40 different metals and minerals. It has to be borne in mind, of course, that very few exploration licences result in mining activities. Globally, 1 out of 1,000 exploration licences leads to the opening of a mine.

Europe struggles to attract exploration investment, most of which is channelled to North and South America, and to Australia. In fact, only about 3% of exploration investment (excluding iron ore) reaches Europe, see Figure 19 (Ericsson, 2023). Reasons for this include complicated permitting processes as well as a lack of knowledge of the geological potential. Most of the exploration investment targeted at Europe goes to projects in Sweden and in Finland.

Figure 18: One interesting project for the potential future mining of minerals rich in REEs is at Norra Kärr, east of Lake Vättern. The picture shows part of the mineralised rock outcrop, with plenty of reddish crystals and aggregates of minerals from the eudialyte group, the main ore mineral in this deposit. The loupes are shown for scale, the largest being 4 cm long. Photo: Erik Jonsson.

For junior companies, access to capital is often a limiting factor in developing new deposits. Many of these companies rely on venture capital in various forms to run their operations and are therefore highly dependent on the state of the economy, metal prices and the risk investment climate in various capital markets. To stimulate exploration outside the large mining companies and to influence the direction of exploration for strategic metals, Sweden should consider some form of governmental intervention for exploration

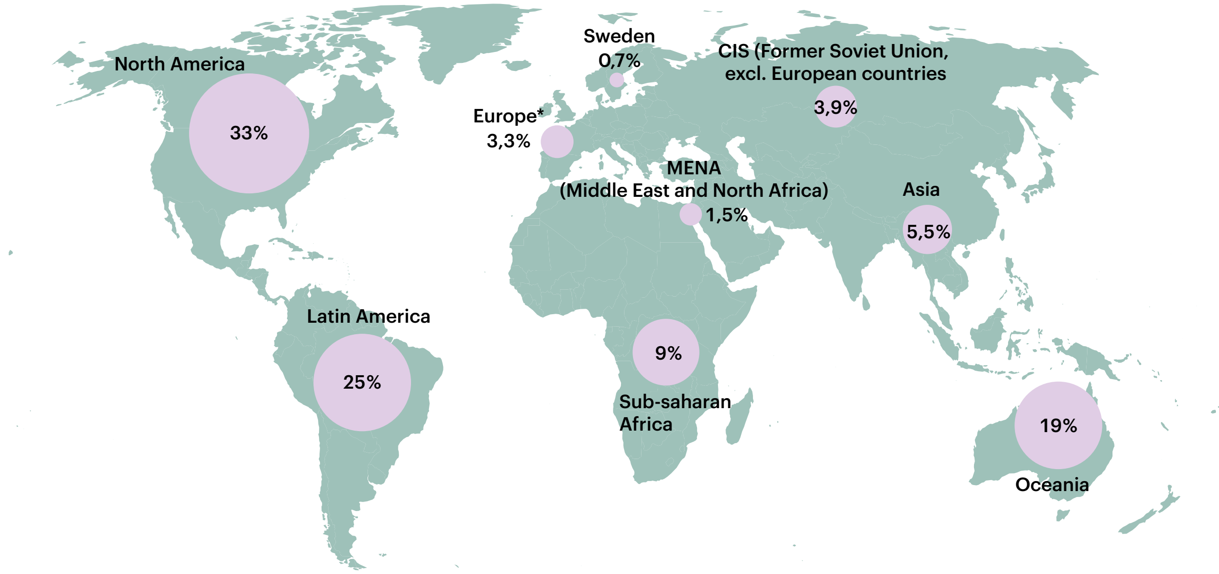


Figure 19: Distribution of investment in exploration in the world in 2022. The figures do not include exploration for iron ore. If this is included, Sweden's share of the total grows to around 1.2%. In total (including iron ore) over US$14 billion was invested in 2022, an increase of 16% compared to 2021. Source: S&P Global.

in the same way as is done in Finland and Japan. Similar initiatives used to exist in Sweden, in the 1960s and 1970s.

Exploration projects targeting critical raw materials that are now progressing well in the permitting process to establish a mine include the graphite deposit at Vittangi in Norrbotten. The presence of REEs has also been demonstrated in several places, for example at Norra Kärr, east of Lake Vättern. LKAB is aiming to extract REEs and phosphorus as by-products from its existing iron-ore operations and has also identified a new deposit, Per Geijer, for possible future mining if a licence is granted.

However, challenges related to insufficient knowledge about critical metals and minerals, their occurrence and formation processes, as well as various metals' host minerals and general geological positions, mean that there is still a long way to go before Sweden's full potential for them is likely to be realised.

Viewing geology and exploration in terms of innovation

Exploration is a value chain that needs to be developed. It is based on science and basic research in geoscience and geophysics. To manage the new demand for metals, greater expertise and innovation in prospecting methodology must be developed in Sweden, such as the use of advanced geophysical technology on aircraft, helicopters and drones, and for drill core scanning.

Integrated knowledge of bedrock geology, mineralogy and geophysics is crucial for successful exploration. It is also important to develop theories and models for ore formation in order to predict the location and extent of deposits. The lack of sufficient research in ore geology and ore mineralogy is a problem in Sweden, and the focus needs to be expanded to critical metal and mineral-bearing systems and the challenges associated with lower metal grades.

Loss of skill and reduced mapping threaten exploration efforts

Regional geological knowledge is necessary for training future geologists, for geological mapping and for research into Sweden's mineral deposits. Up-to-date geological information is also essential for meaningful exploration; maps and data have a limited shelf life and need to be regularly updated using new technologies.

Today, expertise in Swedish geology at universities is declining, which threatens geo-education and activities that need these skills, especially in exploration and mapping. The situation is acute as fewer and fewer researchers and teachers are choosing to focus on Sweden's geology. In addition, the Swedish Geological Survey (SGU) is suffering from a loss of capability in regional geology and is carrying out far less geological mapping than before.

Mining in Sweden today

Details of Sweden's 13 active metal mines are shown in Table 1. Five of them produce iron ore; the others base metals, and gold and silver. Apart from copper, no critical metals or minerals on the EU's list are now mined in Sweden. In addition to its metal mines, the country has almost 30 that produce industrial minerals.[2]

The current 13 metal mines can be compared to the 260 that were in operation in Sweden at the end of the First World War, see Figure 20. Although the number of mines has fallen significantly since the middle of the last century, production has more than quadrupled, from around 20 million tonnes of ore (iron and non-iron) in 1953 to almost 90 million tonnes today (SGU, 2023). The Aitik open-pit mine has doubled its production, and the Kiruna and Malmberget underground mines have also increased their output.

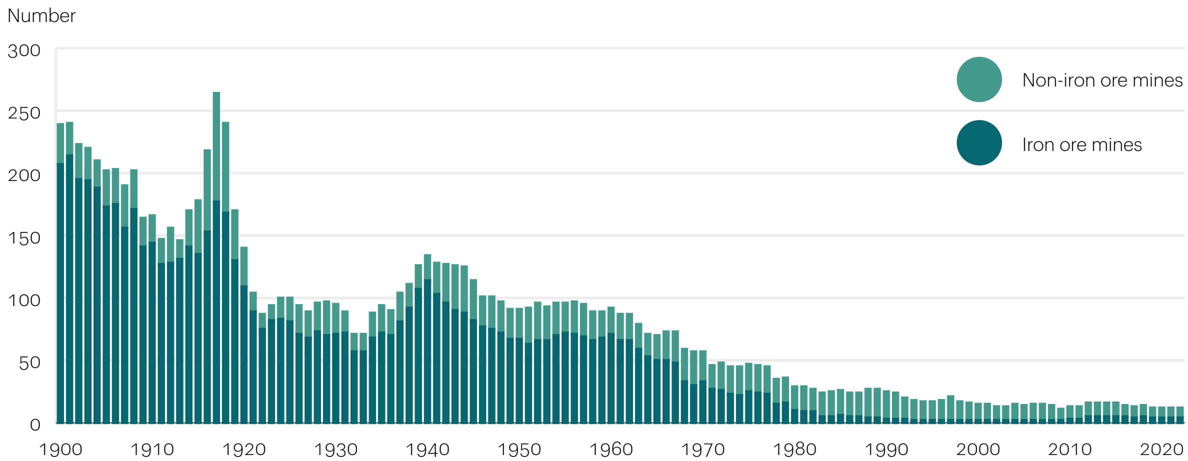
Table 1: Sweden's 13 active mines in 2022.
Source: Statistics of the Swedish Mining Industry, SGU, 2023, Botnia Exploration, 2024.

Company	Mine	Ore/Metal
LKAB	Malmberget	Iron ore
	Kiirunavaara	Iron ore
	Svappavaara	Iron ore
Kaunis Iron	Tapuli	Iron ore
Lundin Mining	Zinkgruvan	Zinc, lead, copper, silver
Lovisagruvan	Lovisagruvan	Zinc, lead, silver
Boliden Mineral	Garpenberg	Zinc, lead copper, silver, gold
	Kristineberg	Copper, lead, zinc, silver
	Renström	Copper, lead, zinc, silver
	Kankberg	Gold, tellurium
	Aitik	Copper, gold
Mandalay Resources	Björkdal	Gold
Botnia Exploration	Fäbotjärn	Gold

Something all Swedish mines have in common is their high productivity on a global scale, whether they are very large, like the ones mentioned here, relatively small, like the mines in the Skellefte field, or really small, like the Lovisa mine in Bergslagen, see Figure 14 and 16. Most of the mines have been active for a long time, often for many decades. The Garpenberg mine dates from the Middle Ages, Zinkgruvan and the Malmberget iron-ore mine started in the 19th Century, and Kiruna opened in the early 20th Century. All of these mines have historically been associated with further processing in steel mills or in base-metal smelters and refineries. This connection has always provided a competi-

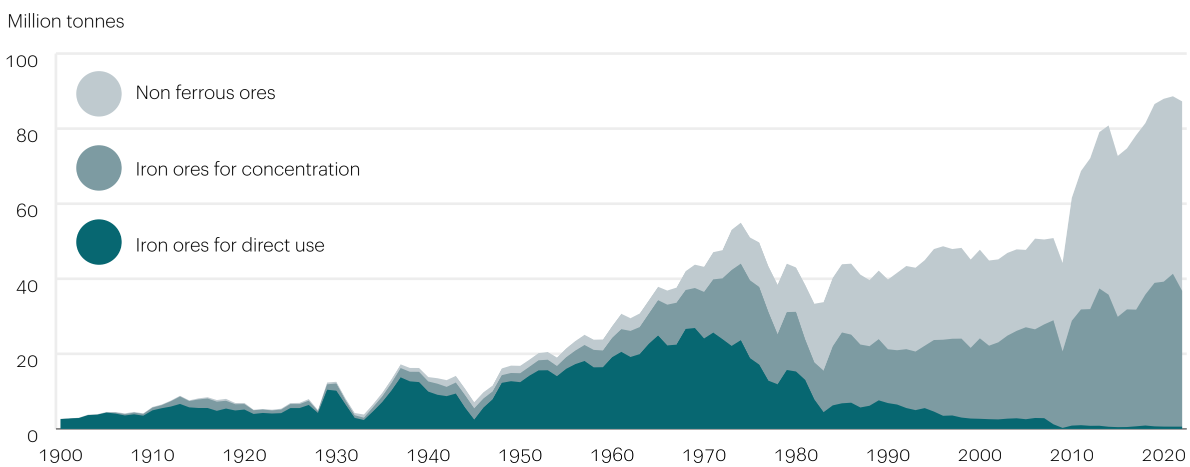
2 For example, graphite, quartz and lime.

Figure 20: Number of mines in operation in Sweden 1900–2022, split into iron ore mines and non-iron ore mines. Source: SGU's Mining Statistics 2023.



Number of mines in operation 2022
Non-iron ore mines = 8
Iron ore mines = 4

Figure 21: Ore production in Sweden 1900–2022, split into iron ore and non-iron ore. Source: Statistics of the Swedish Mining Industry 2022, SGU 2023:1.



Ore production in Sweden
Non ferrous ores = 50.5 Mton
Iron ores for concentration = 36.2 Mton
Iron ores for direct use = 0.6 Mton
Totalt = 87.3 Mton

tive advantage, even though ore is also exported or imported when profitable. The recent increase in production has resulted from large-scale and cost-effective mining with new, more productive machinery in both open-pit and underground mines.

Sweden's smelters

Several active steel producers in Sweden process iron-ore products into iron and steel products: these include Höganäs, SSAB, Outokumpu, Alleima and Ovako. Alloy metals are often imported from other countries. One exception to this is the Turkish-owned Vargön Alloys smelter at Trollhättan, which produces ferrochrome from imported chromite concentrate.

In addition to the ironworks and the ferrochrome plant, Sweden's two primary smelters are the Boliden-owned Rönnskär copper smelter in Västerbotten and the Kubal aluminium smelter at Sundsvall, which is part of Russian oligarch Oleg Deripaska's world-leading Rusal aluminium company. Boliden's large Bergsöe secondary lead smelter, located at Landskrona, is the Nordic region's only producer of recycled lead from traditional car batteries.

Copper is the principal product at Rönnskär, as well as gold, silver, lead, zinc and sulphuric acid, from ore concentrates originating from both Boliden's own and other operators' mines and processing facilities. Rönnskär is also one of the world's leading plants for recycling metals from electronic scrap. In 2021, the company inaugurated a hydrometallurgical plant as part of its effort to recover more of the metal contained in by-products such as gas-cleaning dust and sludge that are generated continuously at Rönnskär. Boliden also owns two smelters in Finland (Harjavalta and Kokkola) and one in Norway (Odda).

To meet future demand, metallurgy will need to be able to handle lower-grade ore concentrates and to extract more metal from complex ores. New technology and methodology may also be needed to mine smaller orebodies, those that are currently left behind. More efficient processes and fossil-free reducing agents are also required.

Regarding hydrometallurgical methods applied to critical raw materials, there are several examples of initiatives in Sweden and the Nordic region that have already been launched or are close to it, in both time and implementation.

Talga AB has been granted permission to extract graphite ore at Vittangi and thermochemically refine it into graphite anode material for lithium-ion batteries (Talga, 2023). The company emphasises that one of its challenges will be the transition from laboratory scale to pilot plants and then to the industrial production of graphite anodes.

LKAB's ReeMAP project at Luleå is aimed at extracting critical raw materials from mining waste. Working in collaboration with Luleå University of Technology and local industry, LKAB aims to establish a centre for the chemical engineering industry to develop methods for extracting mineral fertiliser, REEs, gypsum and fluorine. The materials will be extracted from tailings from iron-ore production at the Kiruna and Malmberget mines, the tailings having undergone a further processing step to produce an apatite concentrate before being deposited in tailings dams. This concentrate will be transported by rail to Luleå Industrial Park for further refining using hydrometallurgical processes that involve dissolution in hydrochloric acid and the separation of fluorine, phosphoric acid and mixed rare-earth oxides. These oxides will then be sent to Norway for separation into individual metals. The plant is planned for operation in 2027 (LKAB, 2023).

To summarise, several activities are already under way, but major challenges remain. While technological development is very important for increasing the efficiency and sustainability of all types of metallurgical processes, at the same time the development of knowledge and training, new business models and material flows is needed so that Sweden can process and refine its own mineral resources when new deposits come on stream.

Permitting processes

Permitting processes play a central role in the discussion on how the increased demand for metals and minerals should be met. This applies both to their appropriateness in Swe-

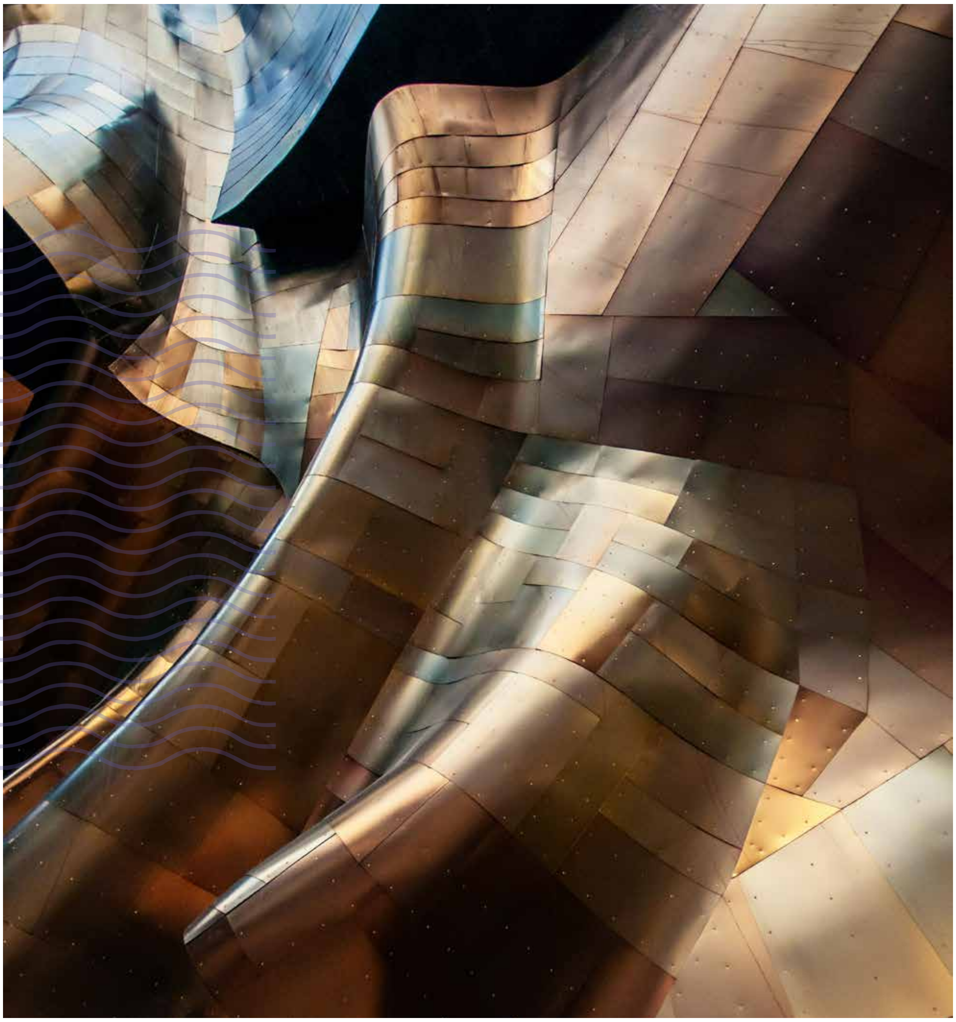
Figure 22: Illustration of the Nordic mining 'cluster': Nordic and international companies operating in Sweden, Norway and Finland. Source: RMG Consulting, 2024.

den and other countries within the EU, as well as to how differences between various countries in the international market affect competitive conditions between companies in different markets.

From a societal perspective, the permitting processes are democracies' way of managing environmental risk in both the short and long term, resolving conflicting objectives, and managing conflicting interests. The processes always end in a decision where the actual considerations, often made over a long period of time, can be analysed afterwards.

Viewed in this context, as the function of making difficult trade-offs between different societal interests, it is natural for permitting processes to be debated and questioned. Today, they are criticised for taking too long, for not being able to manage trade-offs between local and global environmental benefits, and for not being sufficiently open to necessary compromises between different interests. Various stakeholders often express a desire for politicians to take a step forward and act more decisively.

One of this project's expert groups addresses Sweden's permitting processes specifically, with the ambition of providing as accurate a description of the current situation as possible. Their focus is on highlighting the actual possibilities and limitations that exist today from various stakeholders' points of view. The expert group's main task has therefore been to create a basis for proposals for improvements, respecting the many difficult trade-offs between different societal interests such changes require. For further details, see the forthcoming report '*Increased Demand for Metals and Minerals – Conflicts of Objectives and Interests*' within the IVA's Roadmap for Metals and Minerals project.



9. Definition of critical raw materials and their complex market

»Most critical metals are by-products of base metals that are extracted in larger volumes. This makes for a complex market.«

There is no universal, unambiguous definition of critical raw materials. The definitions used today usually refer to metals and minerals that have not previously been used to any great extent and are therefore relatively uncommon or rare, not least in terms of extractable resources. They should also be of high economic importance for a particular industry, industrial sector, or geographical area.

Many critical metals are characterised by the fact that they are rarely produced in large volumes globally, and/or that they are rarely included in products in significant quantities compared to steel and the base metals copper, zinc, lead and aluminium. However, they often constitute essential components where substitutes are not usually an option, as it would involve shifting the supply problem from one critical raw material to another, or impairing performance.

Global demand for traditional metals, such as iron (steel) (2,000 Mt/year), aluminium (70 Mt/year) and copper (20 Mt/year), differs markedly from the demand for the most critical raw materials. Demand for these is on a completely different scale: for instance, REEs (200,000 t/year), cobalt (150,000 t/year) and platinum group metals (400 t/year).

The EU has also introduced the classification of 'strategic materials', which holds particular relevance for strategic technologies related to the green transition, digitalisation and defence. Similar definitions have been developed in other countries and regions.

See info box on the right.

DEFINITIONS

Metals and minerals are divided into different categories and given different names based on different purposes. Categorisation varies between countries/regions. Examples of classifications within the EU are:

Critical materials: A raw material is defined as critical if there is a significant risk of supply disruption and it has a significant impact on the economy.

Strategic materials: A raw material that is crucial for the green and digital transitions and/or in defence and space applications. All strategic materials are also defined as critical.

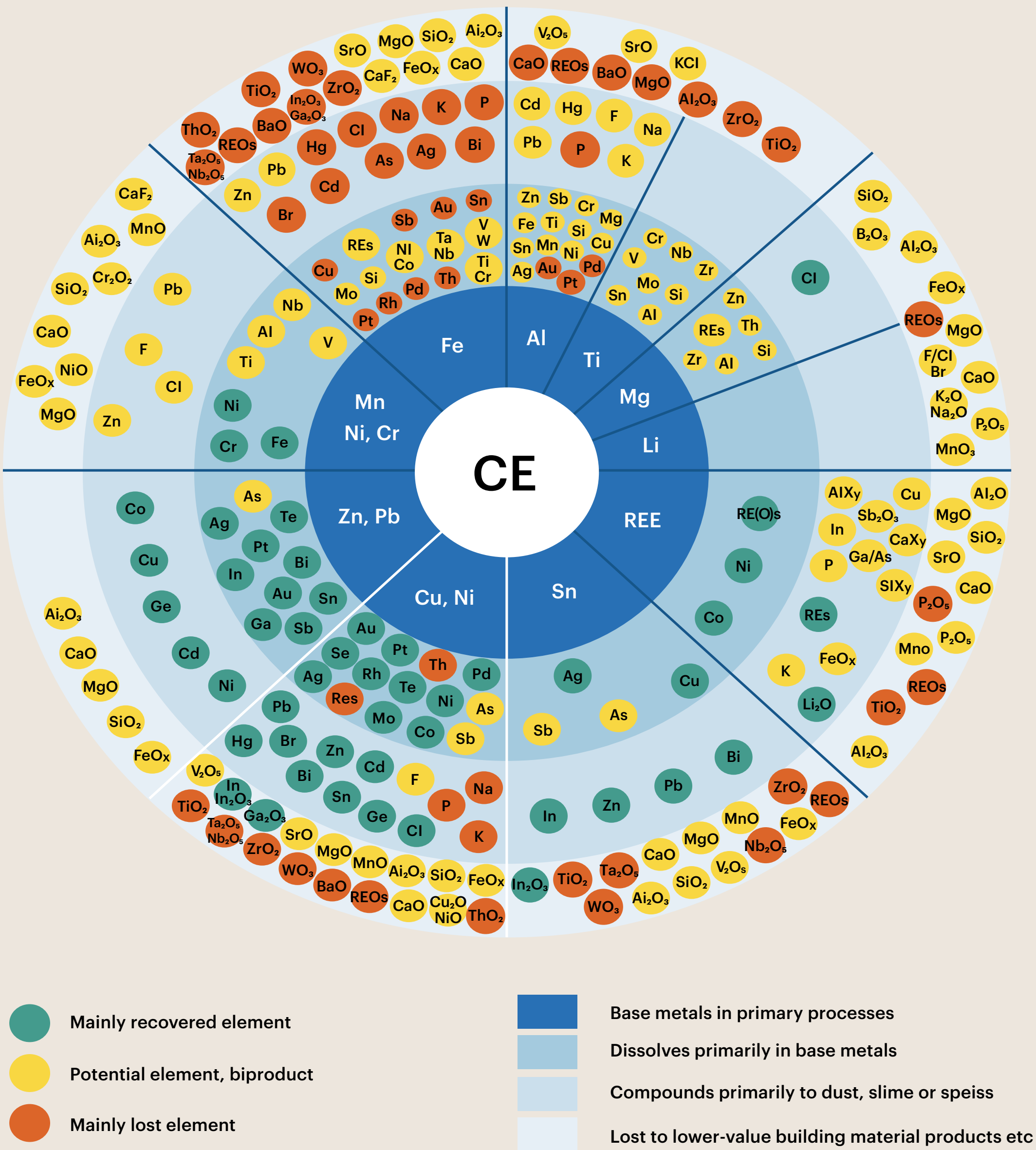
Position in the periodic table: The scientific classification of metals as elements is based on their physical properties and position in the periodic table.

See the glossary for more about the different categorisations of metals and minerals.

Complex markets for several critical metals

As mentioned before, several of the critical metals are by-products from large-scale base metal mining. They occur in low concentrations in ores together with the base metals, and therefore rarely or never form their own mineable deposits with current technology and price levels.

Figure 23: The metal wheel shows how various metals are found in connection with different types of ores (oxide and sulphur compounds are the most common), and the by-product metals that can be associated with different types of base-metal mineralisation. Source: Reuter, van Schaik, Gutzmer, Bartie, & Abadias-Llamas, 2019. See also the periodic table on page 14 for deciphering the chemical symbols.



When they are extracted, it is as by-products in the later stages of the metals' production chain, in smelters or during metal refining through, for example, leaching and chemical separation. If the by-product metals can be extracted at a profit, they generate an increase in the value of the ore, but they can also cause problems that increase production costs. The extraction of the by-product metals often requires investment in sophisticated processes. Since the volumes of these metals are small compared to base metals, it can be difficult to make any investment economically viable for an individual company. For this reason, many of the metals society might need today can be found unused in mining waste such as waste rock piles or slag dumps.

The low volumes also mean that it is not profitable to mine these critical metals without extracting the main metal from current deposits. For example, cobalt is present in many ores, together with nickel and copper. In simple terms, increased extraction of cobalt therefore occurs in conjunction with increased production of nickel or copper. Another example is vanadium, which is extracted together with iron ore. In the long run, this means (somewhat simplified) that the extraction of cobalt and vanadium is largely controlled by the market for nickel and copper and iron respectively – or that demand for the by-product metals, if the price gets high enough, affects the market for the base metals (Jonsson, 2021).

For this reason, only a small proportion of any by-product metal is normally recovered (Fu, Polli, & Olivetti, 2018) and in general, only a small proportion of the by-products contained in a mine's ore output is likely to be separated out using current technology and prices. Even at this lower level, there is potential for supply that exceeds current demand, but no data are available to determine exactly how much of all by-product metals could be recovered. For example, theoretical calculations on the global level for gallium and germanium indicate that the potential is about ten times higher than what is currently separated (Frenzel, Mikolajczak, Reuter, & Guzmer, 2017).

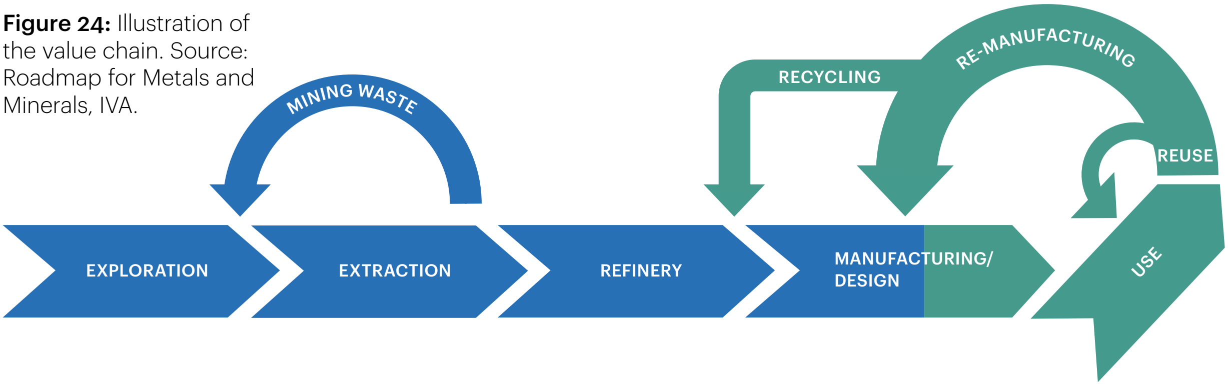
For indium, the potential is much lower, but it is still three times greater than current production. It is not clear exactly why more of the mineral value is not extracted: the explanation is probably a combination of low-profit margins for the producer and the high-risk new investments required. The environmental impact of these processes and the associated licence requirements may also constitute obstacles.

The dynamics between supply and demand are therefore complex. Supply is often relatively inelastic, meaning that even if demand increases and the price for the critical metal rises, the production of the metal will not increase; at least not in the short term. Instead, increased production of the critical metal is influenced by the demand and production of its main metal. All base metals are traded in large volumes and priced on metal exchanges worldwide. On the other hand, most critical metals are priced in a non-transparent manner with limited visibility and control (Reginiussen & Hallberg, 2018).

10. Overview of the value chain for metals and minerals

»Having a mine is not enough. You also need access to refining processes to be able to produce the pure metal and key components.«

Figure 24: Illustration of the value chain. Source: Roadmap for Metals and Minerals, IVA.



The value chains for metals and minerals begin with fundamental geology and exploration and, in an optimal system, end in the recycling of a sustainable product. This report discusses the supply of metals and minerals, from extraction or recovery from mining waste to the production of essential components needed for industrial development and a sustainable transition. Reuse and recycling are discussed in greater detail in the project's second report, *'Circular Flows to Meet Increased Demand for Metals and Minerals*'. Figure 24 illustrates the value chain discussed in these two reports.

Exploration

Exploration is the search for economically recoverable deposits of metals, minerals and other natural resources through geological, geochemical, mineralogical and geophysical surveys. It is a necessary foundation for any mining operation and requires extensive fieldwork, sampling and analysis. Exploration also provides important knowledge about the bedrock and the geology of the region. It is a complex and lengthy process that requires expertise and extensive surveys over large areas, which makes it very cost-intensive.

Only a small fraction of all exploration efforts develop into a working mine. Once a potential ore body is found, it can take up to tens of years to drill, analyse and collect more information on its composition and distribution. Despite often receiving large-scale investment, in the end very few projects lead to producing mines. Obstacles along the way may be that the deposits are too small or low-grade, that prices are too low during the period in question, or that it is difficult to obtain permits for environmental reasons (SGU, 2023). Economic mineralisation – ore in the strictest sense – is therefore to be considered a rarity.

Environmental aspects of exploration

Exploration typically does not have a significant impact on the natural environment, but this varies depending on the terrain in the survey area, the thickness of the soil cover and the techniques used. Examples of environmental impact include tree clearing, vegetation disturbance during terrain driving and temporary effects on surface and ground water during drilling. Sound and light conditions are also affected.

To prevent and minimise negative environmental impact, exploration should be carefully prepared by checking soil conditions and vegetation, finding suitable transport routes and identifying sensitive areas and objects (Svemin, 2018).

Mining

A mine is a location where ore, minerals or other natural resources are extracted. Mining can take place above ground, in so-called open-pit mines, or underground. A mine is often combined with a mineral-processing facility where the raw ore is upgraded into concentrates or pellets for further treatment at smelters and, later, at refineries. See also the section *Mineral processing* below.

Once a mineral deposit has been found, a mining permit is needed from the Mining Inspectorate of Sweden (Bergsstaten) and an environmental permit from the country's Land and Environmental Court (Mark- och miljödomstolen). For a more comprehensive overview of Sweden's permitting processes, see the forthcoming report '*Increased Demand for Metals and Minerals – Conflicts of Objectives and Interests*' where these are discussed in more detail.

Establishing a mine is a time-consuming process. Starting from geological and technical data, a suitable mining method (either open-pit or underground) can be selected. In general terms, low-grade, high-volume deposits are extracted in open-pit mines, while deeper, higher-grade but smaller deposits are mined underground. Different mining methods can also be adapted depending on the geological conditions.

Mining operations require infrastructure for energy supply, roads for transporting materials and equipment, and buildings for various activities. They also require facilities to manage water flows from various processes, such as dams and water-treatment plants. In addition, mines depend on a skilled labourforce and housing in the surrounding area to operate efficiently.

Infrastructure around the mine is also important for operations. One example is the Iron Ore Line, the railway between the port cities of Luleå and Narvik (whose capacity is sometimes insufficient), or access to a road network that can manage heavy vehicles. Proximity to electricity supplies also affects the potential of mining operations.

Mineral processing

Mineral-processing plants are usually located close to a mine to avoid having to transport large quantities of heavy, low-grade material over long distances. In the plant, ore is crushed and ground into fine sand to permit the separation of target minerals from other material. The ore minerals are then separated out using physical and chemical methods.

The process requires a lot of water, which is treated and recirculated; the extent to which this is done varies from site to site. The tailings that remain after separation may contain minerals and elements that are potential contaminants, such as sulphide minerals. Copper, zinc and lead often occur naturally with sulphur as sulphide minerals (see Chapter "Definition of critical raw materials and their complex market"), with tailings being deposited in tailings dams to protect the environment. The material is kept saturated with water to prevent its exposure to oxygen and the weathering of sulphide-rich minerals to form sulphuric acid – which can leach out residual metals. At the same time, elements that are water-soluble, such as salts, may also leach out. For this reason, it is crucial to know the mineralogy of the ore and the surrounding rock. Stringent requirements are placed on a tailings-dam's construction to prevent it from bursting under the pressure of tailings and water, with dams being equipped with monitoring systems and sensors. Another challenge is that the tailings dams occupy large areas of land.

Dry waste storage can be used as an alternative to tailings dams. This occupies less space and is safer by reducing the risk of dam failure. It is unclear, however, whether dry storage is suitable for Sweden's climate, so more knowledge and technology development are needed to find alternative cost-effective solutions that can suit Swedish conditions.

Environmental aspects of mining and processing

Mining ore to extract metals and minerals has an impact on the local natural environment and the global climate. Much can be done to minimise environmental impacts during operations, and to create conditions for restoring the soil and vegetation after a mine has closed. This requires a holistic approach to the entire production chain. For example, it is important not to focus solely on the climate aspects. Biodiversity and water quality also need to be highly valued in analysis and planning.

A mine itself affects soil and hydrology, which in turn affects vegetation and wildlife. Facilities and processes in the area require not only energy and water, but also resources such as chemicals. The extent of any environmental impact depends both on the natural environment and the type of mineralisation in the area, and whether it is an underground or open-pit mine. The environmental impact also varies depending on the mining methods used, the energy supply, the chemicals used in the process, the techniques used for water recycling and purification, and how the waste is managed.

There are major differences in the conditions for preventing or remedying environmental impacts, depending on whether it is a question of:

- ongoing operations in an existing mine;
- a new mine or an expansion to an existing one; or
- historical waste from previous mining operations.

Minimising environmental impacts requires careful planning at an early stage. With better knowledge of the ore and the surrounding rock, it is easier to anticipate and prevent potential environmental risks that may arise from water and waste management if a mine is developed, as well as to design appropriate remediation for when it ceases operation. Planning can also have a positive impact on product quality. The opening of a new mine therefore offers more opportunities for preventive measures. Being able to design a facility for future closure is a success factor.

New types of ore, processes and methods create new types of waste, sludge and pollutants for which there is still a lack of experience and research into their characteristics and behaviour; this may lead to stable metals being released and concentrated in leachates. To make better use of all the materials extracted from a mine, there may be benefits even at the planning stage in exploring potential uses for different residual flows, and whether these can become products instead of waste.

Underground mines do not have the same impact on the landscape as open-pit mines, which often involve extensive changes to the landscape as waste rock overburden is excavated to reach the ore. Whilst this affects vegetation, biodiversity and water flows, the surface material removed, such as soil and peat, can be stored and then reused later to restore the land after operations have ended. Waste rock can also be used for backfilling open-pit or underground mines and, if there are no environmental risks, as a construction material at the mine – for building dams, for example.

Chemicals used in the separation of valuable minerals and for water treatment are consumed in the process and cannot be reused.

Electrification and autonomous vehicles reduce environmental impact

A mine and its facilities are energy-intensive. Open-pit mines often have lower energy consumption per tonne of ore than underground mines. However, when measured per tonne of produced metal, the result is often the opposite. The ore grades and the amount of waste rock that needs to be moved are crucial factors for a mine's energy consumption (Priester, Ericsson, Dolega, & Löf, 2019).

Both electricity and (usually) liquid fuel are needed. The environmental impact of electricity use depends largely on how the electricity is produced and what fuels are used. To minimise climate impact, fossil-free electricity should be used.

Fuel is also needed to work machinery and for internal transport. There is a trend towards electrification and digitalisation in mining with the aim of reducing its environmental impact and improving worker safety. Autonomous vehicles are also being introduced that can be operated remotely from a control room. Using this type of equipment means that less waste rock has to be dug out, cutting energy consumption, and air quality is improved since less fossil fuel is needed once equipment electrification becomes more widespread.

Prevent rather than purify water

A mining facility requires a lot of water in its processes, while water must also be pumped away from both open-pit and underground mines to prevent them from flooding. Sweden has both surface water sources and groundwater that can supply the industry with process water.[3] (IVA, 2021). In other countries, water supply can be a critical factor for the industry's processes, and can influence the choice of methods used.

Water is affected by the surrounding soil, the bedrock, and by human activities. No water is completely unaffected, and both water quality and what affects it must be controlled. It is important to prevent water pollution during mining and any subsequent treatment process so that water can be recirculated and, in some cases, discharged back clean to the environment.

Purifying process water or leachate is often problematic as both can contain many different types of substances that require various treatment routes. All purification processes, in turn, generate new waste (sludge) that must be disposed of. It is important to have good knowledge of the properties of the waste to distinguish and guarantee its long-term stability. The most profitable and long-term approach is to implement preventive measures to minimise any environmental impact at the earliest stage possible. Costs increase over time, while the choice of potential alternative measures decreases.

Reworking mining waste

Mining waste can contain varying amounts of a range of metals and minerals. These might be the target minerals from the ore that was mined, or associated minerals that were not extracted or for some reason could not be recovered. Technological development can change the situation in different ways. On the one hand, it increases the demand for metals that were not previously needed. Conversely, new technologies make it possible to extract metals and minerals contained in mining waste. New, fast and inexpensive analysis technology also makes it possible to sample and analyse mining waste, which may contain substances that are needed today, in completely different ways than before.

The various types of waste can be categorised into waste rock (also known as gangue), tailings and slag. Waste rock consists of host rock and sparsely mineralised ore. Tailings refers to the deposits of finely ground material remaining after mineral processing. Slag is residual material from pyrometallurgical processes, such as smelting. These different types of waste usually contain varying concentrations of different metals (Jonsson, Lewerentz, & Persson, 2023).

Sweden's active metal mines today account for an estimated 85% of all the country's accumulated mining waste. According to information from the companies, reported in waste management plans to the permitting authorities, this waste contains several of the metals and minerals that the EU has assessed as being critical.

Compared to mining, recovering minerals from mining waste avoids the actual mining and crushing/grinding (tailings) stages, but the other steps in the process, such as smelting and refining, remain. If existing technologies are available to extract an element, and the savings in mining costs can cover the costs associated with the other steps in the process, extraction will be profitable. Environmental permits also have to be obtained, of course.

There is a general expectation that it will be possible to recover supplies of some critical metals from historic mining waste. However, it is questionable whether this is realistic, for several reasons. Any metals that can be extracted from this waste will only be available in limited quantities, and their extraction will not significantly reduce the total amount of waste. The excavation of waste requires new methods, such as sludge suction, and there is a risk of collapse or landslides. During extraction, a new disposal fa-

3 Climate change affects the potential water supply for industry, particularly in the south-east of the country.

cility may need to be constructed since a large amount of the original waste will remain as waste even after the extraction process.

Extracting metals from old waste can also be more complex as the ore may have oxidised, minerals may have been coated, or metals may have been leached. This changes the mineralogy, and existing processing-plant systems may not be able to handle it.

Several companies have initiatives under way to explore the possibilities of extracting metals and minerals from mine waste in active mines. There are, however, technical, financial and legal obstacles that limit the possibilities of doing this. New technical solutions and expertise will be needed to recover metals from this source in Sweden's metallurgical plants, which are not yet set up to do so. It may also be difficult to make the investments needed profitable. Potential legal obstacles include issues such as ownership rights, permitting processes, responsibilities for contaminated land, uncertainties about the definition of waste, environmental assessments and regulations for waste disposal (SGU and the Swedish Environmental Protection Agency, 2023). Extracting metals from old mine waste can also be very energy-intensive, and can have climate or other environmental impacts. This means that production from historic waste may not lead to any environmental benefit.

Seabed mining

The possibility of extracting minerals on and under the seabed has received considerable attention on several occasions over the last 50 years. At present, small amounts of minerals such as tin and diamonds are extracted from depths of up to a few hundred metres, while the largest volumes are those of sand and gravel that is extracted close to the shore. Resources of cobalt, copper, manganese and nickel at greater depths (3,000–5,000 metres) are believed to be significant. Big technical challenges are involved and, despite several attempts, no production is yet up and running. Land-based production has so far been easier, cheaper and more profitable. The potential scale of any environmental problems created by production from the deep seabed is still largely unknown. Continued research on seabed environments, and how the problems that may arise can be solved, is important (Löf, Ericsson, & Löf, 2022).

Extraction and refining

After an ore has been concentrated in a mineral-processing plant, the concentrate is then treated further to extract the contained metal. This can be done through various metallurgical processes, either based on melting the concentrate (smelting) or by extracting the pure metal chemically in a wet process. It can also be achieved through combinations of different processes.

Smelting techniques include pyrometallurgy and electrometallurgy. Both of these processes use high temperatures to melt and separate the metal; the difference is in the source of the heat. By contrast, hydrometallurgy uses chemical solutions and water-based processes to extract the metal, sometimes also using electrolysis. The methods chosen depend on the metals to be extracted.

Although there is the potential for mining several of the new metals needed for increased electrification and digitalisation in Europe, there is a lack of both knowledge and the processes required to extract and refine them. Sweden is good at pyrometallurgy and smelting, but the new metals require completely different processes, infrastructure and skills, such as more hydrometallurgy, electrochemistry and chemical separation. New recovery plants are also capital-intensive, especially if designed to produce new metals from low-grade concentrates, and new processes need to be developed. In addition, permitting processes are complex and extensive environmental measures are required.

The environmental aspects of extraction and refining

Environmental impacts depend on several factors relating to the metal being processed, the techniques and equipment used, the waste generated, and how advanced the clean-up measures taken are.

Pyrometallurgy is generally more energy-intensive than hydrometallurgy, as a lot of energy is required to melt ore concentrates at up to 1,200–1,300°C. In addition, various fluxes and slag formers (in the form of chemicals and natural resources such as sand and limestone) are required to prevent the need for even higher temperatures and to draw impurities out of the metal melt and into the slag. These contribute to the climate footprint and other environmental impacts, such as contamination from sulphur, arsenic and other relatively volatile substances from, for example, sulphide ore.

Hydrometallurgical processes generally take place at relatively low temperatures, even at room temperature, but on the other hand require several different chemicals for the dissolution and leaching stages as well as for separation, purification and precipitation.

Components that rely on strategic metals and minerals

Having access to pure metals is simply not enough in order to meet industrial needs and to manage the energy transition. A major challenge lies in the production of the critical components that industry depends on in later stages of production.

The European Commission has identified 15 areas of technology that are particularly vulnerable in relation to their reliance on strategic materials.[4] (JRC Science for policy report, 2023). Examples of critical components considered here include batteries, permanent magnets and semiconductors which, in turn, derive their properties from various metals and minerals. These components are vitally important in the development and operation of fossil-free technologies including electric cars, data storage, wind turbines and fuel cells for hydrogen production.

The EU is largely dependent on imports of these critical components, making European industry vulnerable to disruptions in global supply chains caused by geopolitical factors, trade barriers or natural disasters, for example. See also chapter "Geopolitical aspects of the market for metals and minerals".

The following paragraphs illustrate the EU's dependence on critical components containing strategic metals and minerals, taking batteries and permanent magnets as examples.[5]

Batteries

Batteries are central to the electrification of the transport sector and could play an important role in electricity systems that are based on a high level of renewable generation. Their constituents such as lithium, nickel, manganese, cobalt and graphite are needed to achieve high capacity and efficiency.

Lithium-ion batteries (Li-ion) are the most popular battery technology for electric vehicles, energy storage and a wide range of electronic products on the market today. They have a high energy density, meaning they can store a lot of energy in relation to their weight and size. They have gradually replaced nickel-metal hydride batteries and lead batteries, which are heavier and have lower energy densi-

4 Lithium-ion batteries, fuel cells, electrolysers, wind turbines, electric motors, solar cells, heat pumps, hydrogen for direct reduction of steel and electric arc furnaces, data transmission networks, data storage and servers, smartphones, 3D printing, robotics, drones and satellites.

5 For more detailed descriptions, see for example the report 'Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study' (JRC Science for policy report, 2023)

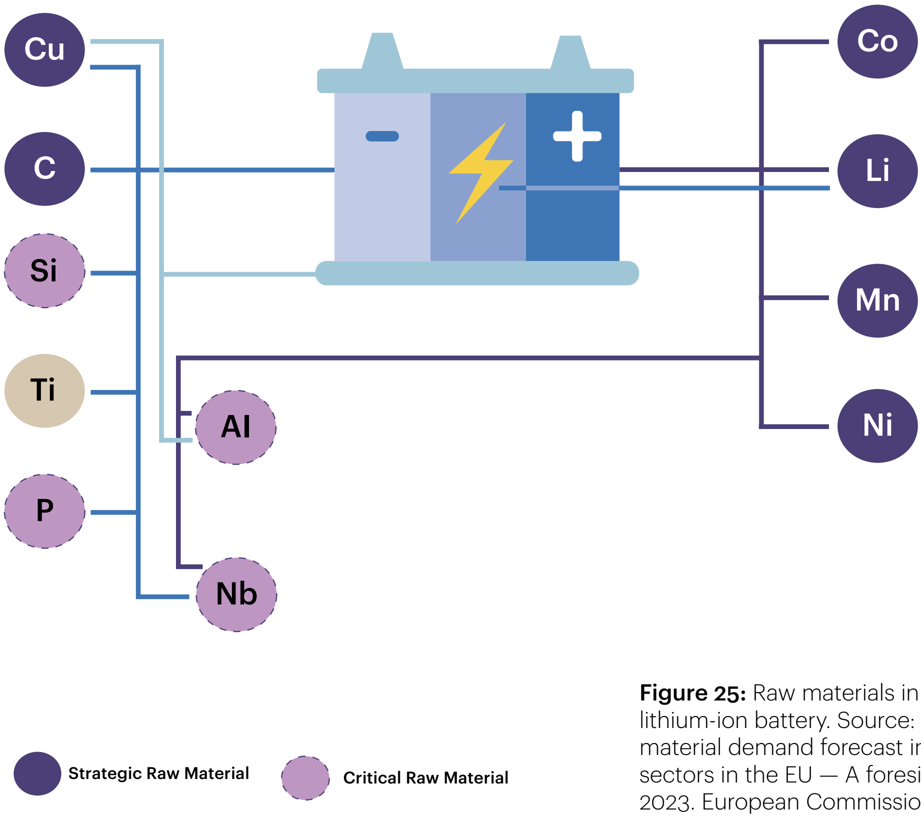


Figure 25: Raw materials in the different parts of a lithium-ion battery. Source: 'Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU — A foresight study', JRC policy report, 2023. European Commission. See the periodic table on page 14 for deciphering the chemical symbols.

ty. Research and development are ongoing into other battery technologies but, according to current assessments, lithium-ion batteries are expected to dominate the battery market for at least the next two decades (JRC Science for policy report, 2023).

The main components of a lithium-ion battery are the cathode, anode, electrolyte and separator. Figure 25 shows the metals and minerals contained in the different parts of the battery.

Europe's lithium-ion battery supply chains are vulnerable. Figure 26 illustrates the vulnerability at each stage (red circles) and the share of European production at each stage compared to global production.

Initiatives now under way to increase self-sufficiency include the Swedish company Northvolt. However, it is not enough to set up a factory for battery production since most of the manufacturing of semi-finished products and raw materials for batteries, as well as their recycling, still takes place in other parts of the world, mainly in China. This means that the entire value chain must be assured, including recycling the material once the batteries are worn out. Northvolt intends to close the loop by recycling end-of-life batteries in conjunction with its factories.

Asia dominates the market for lithium-ion batteries, followed by the USA. Asian companies are also establishing a presence in Europe (examples are Korean companies in Hungary and Poland), but European companies are also

Figure 26: There are risks at every stage of the lithium-ion battery supply chain. Europe's share of global production is shown for each stage. Source: JRC Science for policy report, 2023.

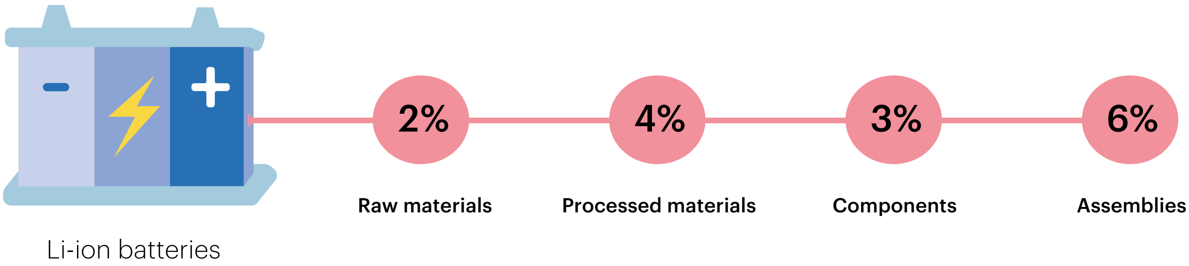
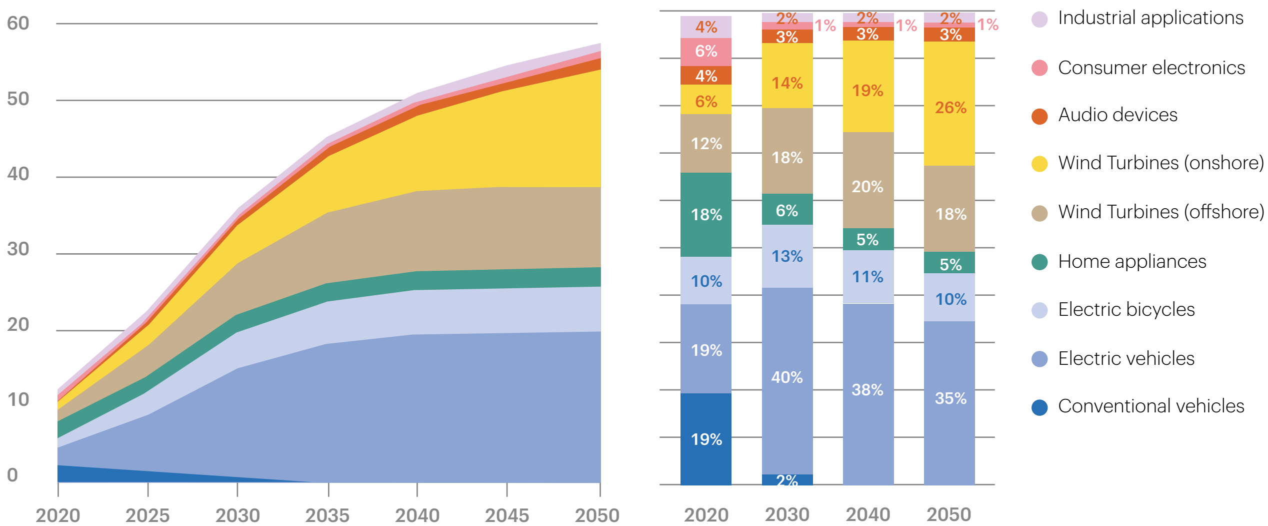


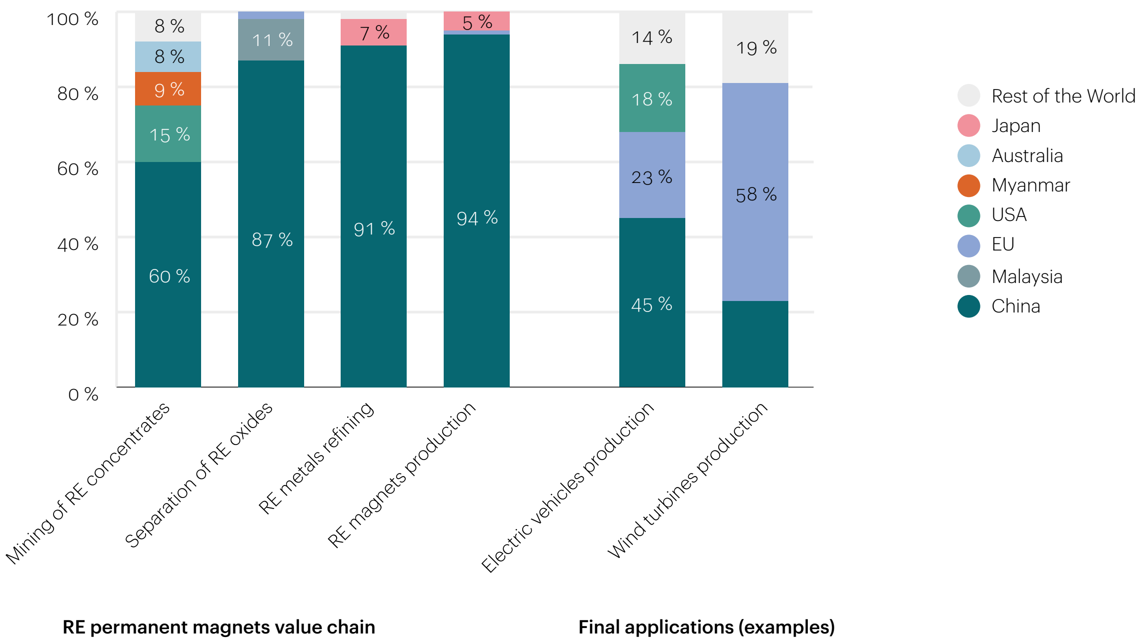
Figure 27: Estimated demand for neodymium-iron-boron (NeFeB) permanent magnets by application. Source: Developing a supply chain for recycled rare earth permanent magnets in the EU. CEPS In-Depth Analysis 2022 (Rizos & Righetti, 2022).



investing in the large-scale production of lithium-ion batteries to meet increased demand.

While China dominates the market for refining and manufacturing batteries, it has significantly less domestic access to the raw materials needed. In 2020, China accounted for 3% of the global mining capacity for cobalt and 11% for lithium. To secure these resources, Chinese companies have entered into agreements with players in the Democratic Republic of the Congo, South America and Australia, and often invest directly in mining companies and projects abroad (JRC Science for policy report, 2023).

Figure 28: The value chain for permanent magnets with the geographical distribution of the different process stages. Source: Developing a supply chain for recycled rare earth permanent magnets in the EU, CEPS In-Depth Analysis 2022 (Rizos & Righetti, 2022).



Permanent magnets

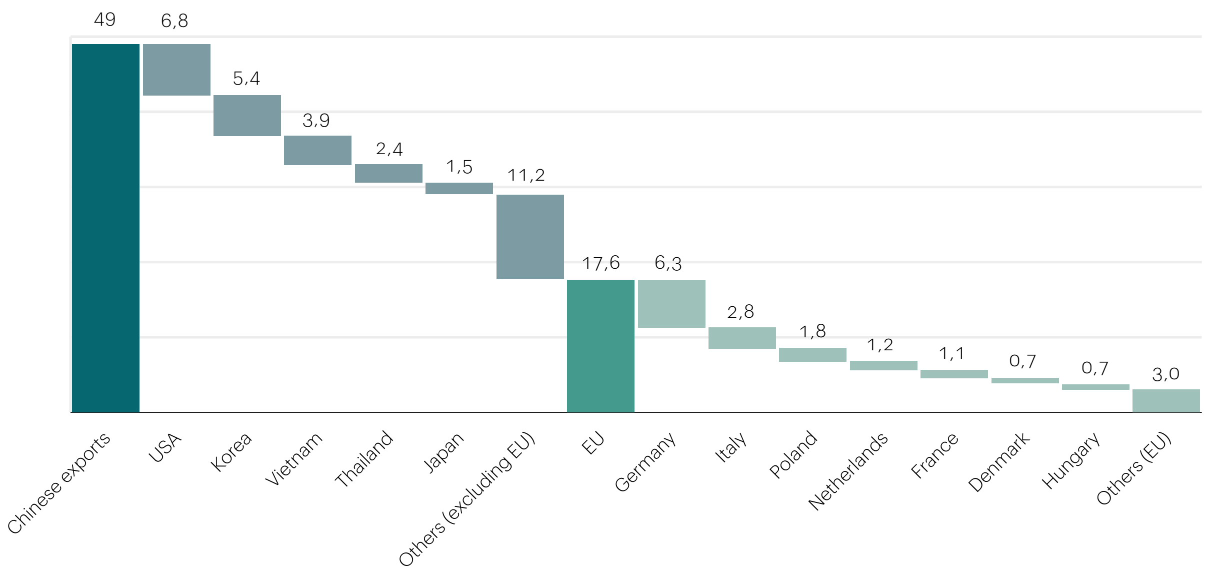
Permanent magnets are used in a wide range of applications, given their ability to produce a constant magnetic field. Wind turbines and electric vehicles are the fastest-growing applications, but virtually all products with an electric motor contain permanent magnets, such as pumps, robots and various household appliances.

Permanent magnets are made of materials with magnetic properties, usually composed of certain alloys or compounds. Most permanent magnets, especially the strongest, contain critical raw materials such as neodymium, praseodymium, dysprosium, terbium, boron, samarium, nickel and cobalt (European Parliament, 2023).

Sintered neodymium-iron-boron (NdFeB) is the strongest and most widely used permanent magnet material. It has a high magnetic strength and energy density combined with low weight and volume, properties that are particularly important in electric cars and wind turbines, and in powerful electric motors in industry. There are also simpler permanent magnets that contain iron or aluminium-nickel-cobalt rather than REEs. These are used in smaller products such as consumer electronics.

Demand for permanent magnets will grow strongly in the coming decade (Rizos & Righetti, 2022). The strongest driving forces are the transition to electric cars and the expansion of wind power. Figure 27 shows how demand for the most powerful permanent NdFeB magnets is expected to increase.

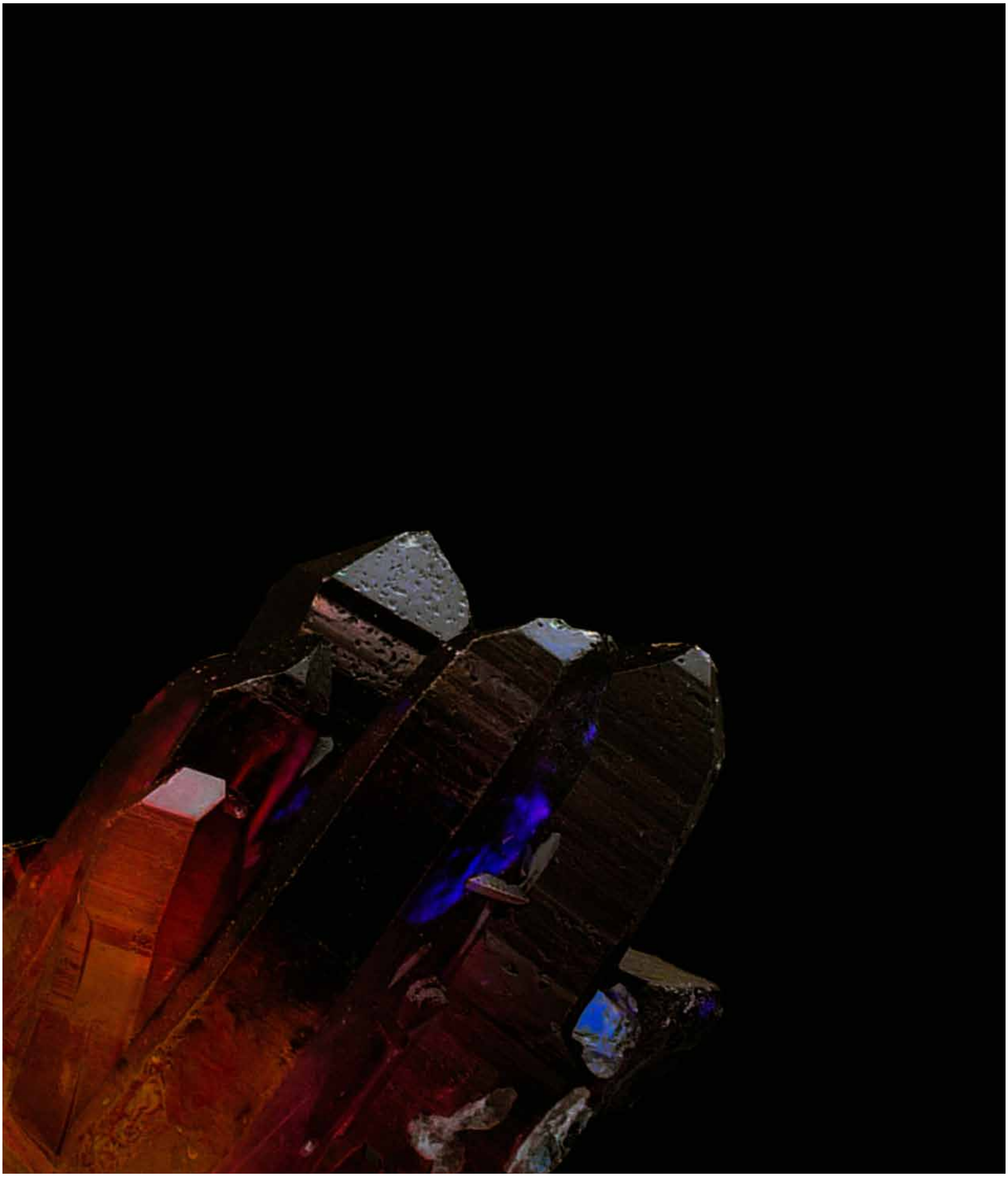
Figure 29: China's exports of rare earth permanent magnets, by importing country (thousands of tonnes) Source: Developing a supply chain for recycled rare earth permanent magnets in the EU. CEPS In-Depth Analysis 2022 (Rizos & Righetti, 2022).

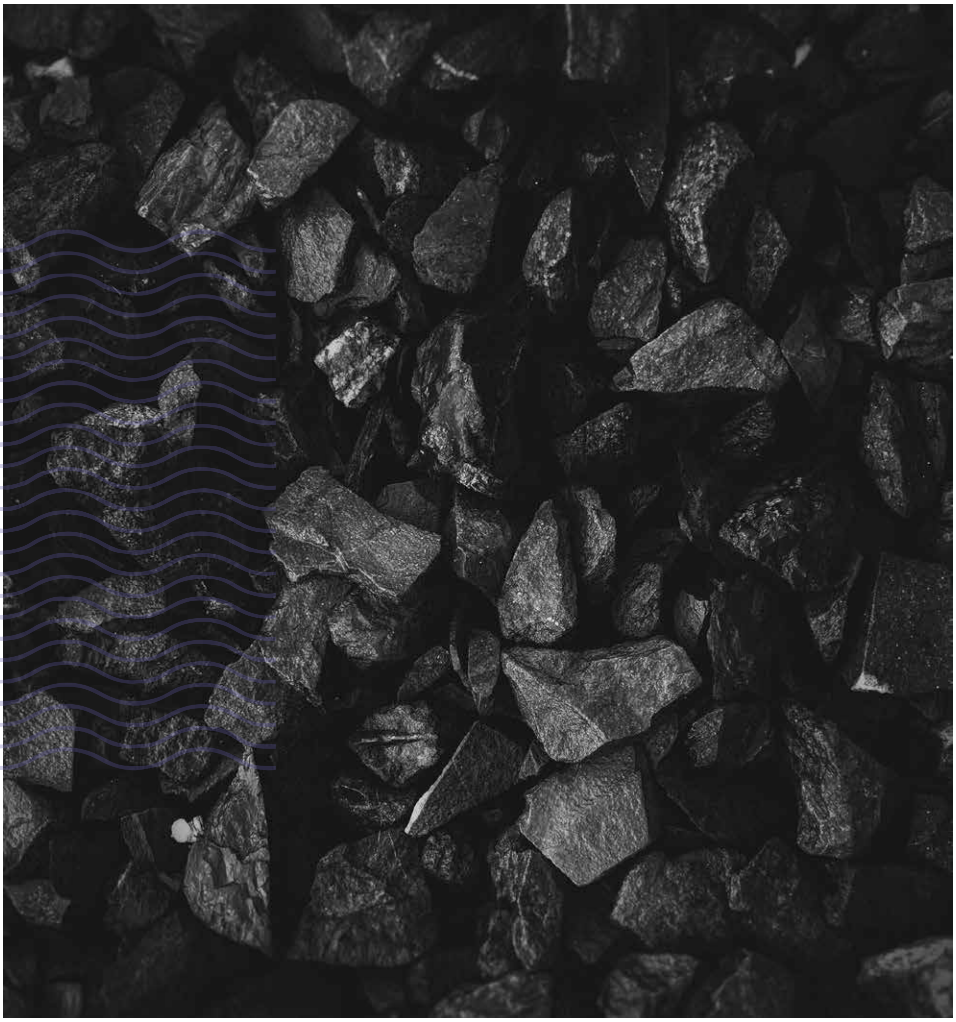


The value chain for permanent magnets can be divided into the generic steps described above: the mining, processing and refining of metals; the production of magnets; and finally production of the final product of which the magnet is part.

China dominates the market for permanent magnets in the entire value chain from mining and processing to the production of the magnets, see Figure 28. There is some production of permanent magnets in Europe, but the bulk of the region’s needs are met by imports, almost exclusively from China. At almost 18,000 t/year, the EU as a region is the largest importer of Chinese NdFeB magnets (Rizos & Righetti, 2022). In total, EU imports account for 36% of China's exports of these magnets, meaning that China controls 98% of the EU market for rare earth permanent magnets. See Figure 29.

There are significant resources of REEs within the EU and Sweden (Rizos & Righetti, 2022), but no magnet manufacturing. The heavy reliance on China for the import of powerful magnets makes the European industry vulnerable to disruptions. At the same time, China's own demand for magnets is also increasing with the growing share of electric vehicles in its domestic market.





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