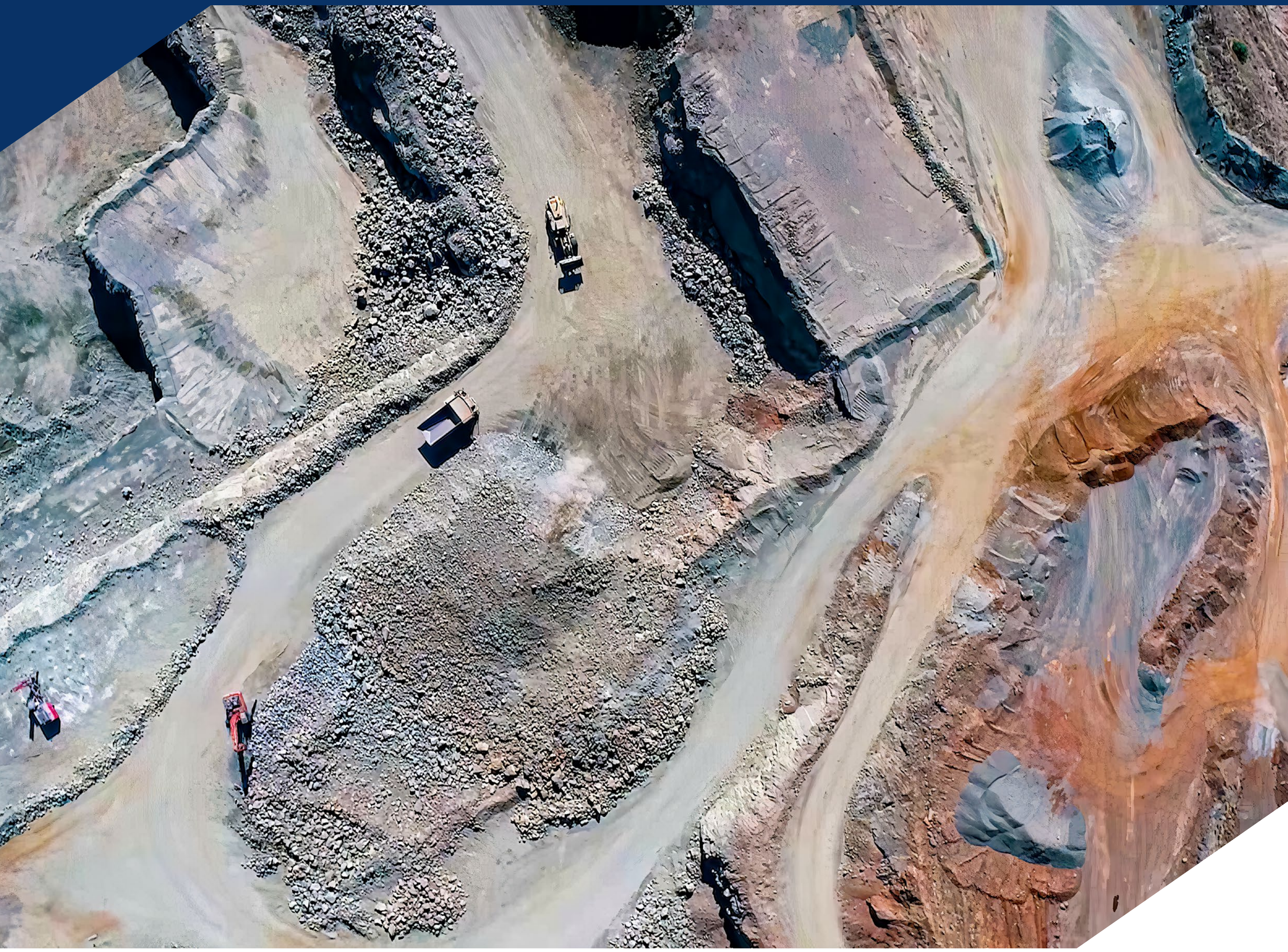
INTERGOVERNMENTAL FORUM on Mining, Minerals, Metals and Sustainable Development

Searching for Critical Minerals?

How metals are produced and associated together



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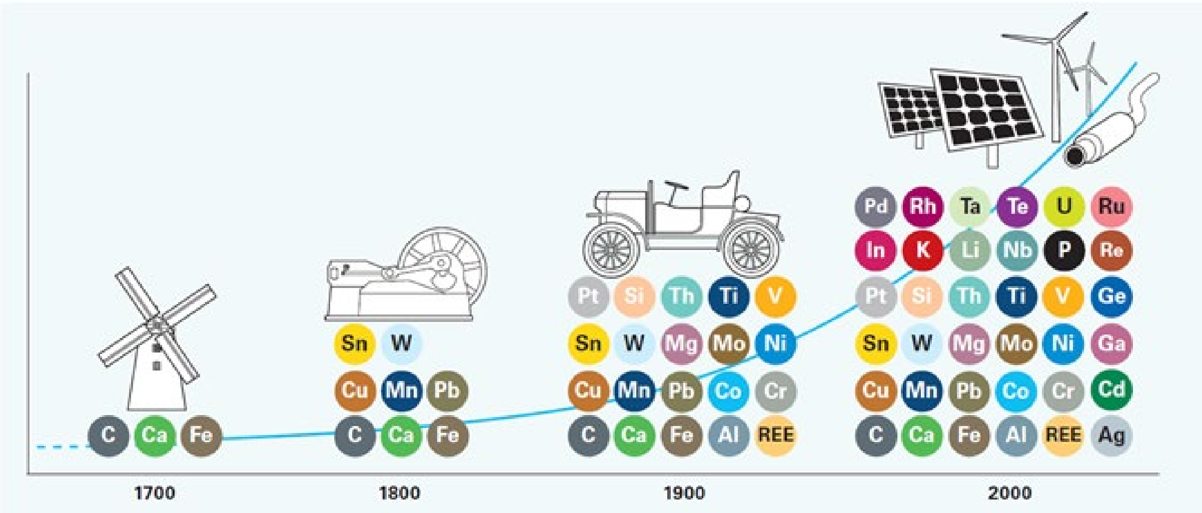
Foreword

This IGF Working Paper is a short technical discussion paper that seeks to explain how metals are produced and are associated together in mineral deposits and mining operations. The aim is to highlight some challenges that may be encountered in the search for minerals that are critical for the energy transition. It is part of a series of knowledge products seeking to better understand the underlying challenges and opportunities connected to the rising demand for minerals and metals and, as such, does not provide any specific set of policy recommendations. These will be developed once the series of working papers is published.

1.0 Metal Use and the Development of Human Societies

Ever since the rise of organized societies, humans have been associated with mining activities and metal consumption. Civilization has always been highly dependent on metals and alloys, from the initial use of copper, then tin (in the Bronze Age), iron and lead (in the Iron Age) in Antiquity—not to mention precious metals such as gold and silver—to the vast array of metals used in our modern world. As illustrated in Figure 1, metal-use intensity in industrial production has increased exponentially over time. Even as our societies have become more sophisticated and complex, we expect the future to be even more mineral intensive, causing demand for more and new metals to grow exponentially.

FIGURE 1. History of main elements used in energy pathways



Note: Position on the time axis is indicative only.
Source: Zepf et al., 2014.

Historically, the six metals previously mentioned (i.e., copper, tin, iron, lead, gold, and silver) were essentially the only ones used (ASM International, 2011) until the major technological breakthroughs in metallurgy in the 19th century. Innovations during the industrial revolution allowed for the identification and separation of a new set of available metals that have since become essential to producing machinery and consumer goods.

BOX 1. DO YOU KNOW WHEN ALUMINUM WAS DISCOVERED?

The Earth's crust is composed of 28% silicon and 8% aluminum, the latter being the most abundant metal in the crust—1,200 times more abundant than copper[1] (Desjardins, 2014). Yet, silicon and aluminum were discovered only in the 19th century.

This relatively recent discovery points to the fact that the difficulty in identifying elements lies not only in their rarity in the Earth's crust—importantly, it is also related to their metallurgical properties, including the link they have with other naturally occurring elements in the Earth's crust.

Today, as the world faces the dilemma of sustaining progress while embracing a change in our modes of consumption in order to reduce and mitigate impacts on the planet, the role of minerals and metals will become more prominent. Two megatrends in particular—the digital transformation and the energy transition—will require more metals than ever before in terms of both quantity and diversity (International Energy Agency [IEA], 2021). Supply will take time to adjust to skyrocketing demand. Some minerals and metals are particularly vulnerable to supply shortages and have been identified as "critical" because of the risks associated with their availability and accessibility.

1 The average aluminium concentration in the earth crust is 8.2%, while the average copper concentration is 0.006%.

2.0 How Are Metals Mined?

Metals are very rarely found as pure elements in the ground. Rather, they are associated with other elements, such as oxygen, sulphur, or carbon, to form minerals.

BOX 2. SOME IMPORTANT DEFINITIONS: WHAT ARE ELEMENTS, METALS, AND MINERALS, AND HOW ARE ORE DEPOSITS IDENTIFIED?

Elements

Elements are atoms that are the basic building blocks of the universe. They are characterized by a specific number of protons and neutrons in their core and have their own specific physical and chemical properties. The number of protons (also called the **atomic number** usually represented by the letter "Z") defines their position in the periodic table shown in Figure 2: hydrogen (Z=1), carbon (Z=6), oxygen (Z=8), iron (Z=26), copper (Z=29) and gold (Z=79) are all elements.

Minerals

A mineral is a solid and inorganic natural material composed of one or more chemical **elements** that have a specific orderly internal crystalline structure. Minerals are classified according to their shape, crystal structure, and chemical composition. Minerals are the building blocks of rocks. Common minerals include quartz, feldspar, mica, amphibole, olivine, and calcite.

Rocks

A rock is an aggregate of one or more **minerals**, whether homogeneous or not. It is classified according to its mode of formation (sedimentary, volcanic, or metamorphic), its chemical or mineralogical composition, or its mechanical properties. Common rocks include granite, basalt, limestone, and sandstone.

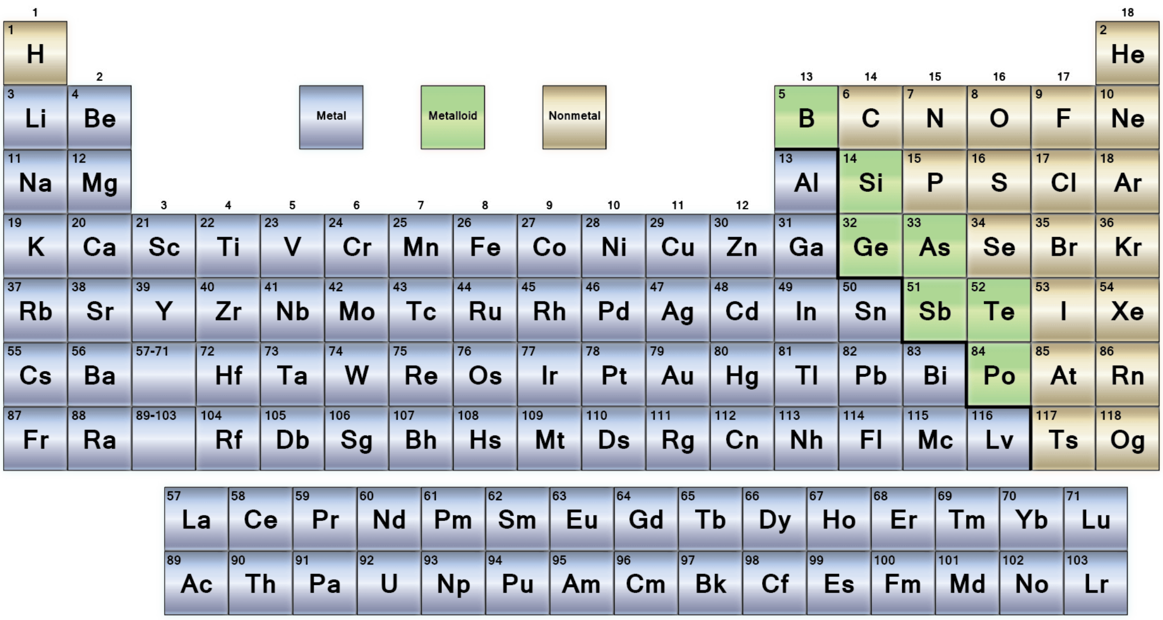
Metals

Metals are a specific set of **elements** (i.e., atoms) that have identified and specific characteristics that differentiate them from non-metallic elements. They are crystalline when solid and naturally occur in **minerals**. They are often good conductors of electricity and heat. They are shiny and malleable. Even if not the most abundant on Earth, metals are the **most represented** elements in the periodic table, with almost 86 metals and 7 metalloids among the 110 elements whose properties have been studied (Figure 2). Metalloids, or semimetals, which are displayed in green, have intermediate properties between metals and non-metals. Metals include iron, gold, silver, aluminum, and copper.

Mineral and Ore Deposit

A mineral deposit is an aggregate of **minerals** in an unusually high concentration. For every mineral deposit, there is a set of conditions, such as the level of concentration and the size of the deposit, that must be reached if the deposit is to be worked at a profit. A mineral deposit that is sufficiently rich to be worked at a profit is called an ore deposit, and in an ore deposit, the assemblage of ore minerals plus gangue[2] is called the ore. An **ore deposit** is an economic term, while a **mineral deposit** is a geologic term (Skinner, 2022).

FIGURE 2. Periodic table of the elements



Note: The periodic table shows the atomic number of each element. Elements highlighted in blue are metals.

Source: Clemson University, Department of Materials Science and Engineering.

2 The mineral elements without commercial value surrounding or closely mixed with the "wanted" mineral in an ore deposit is known as gangue.

The four major metals extracted since Antiquity—i.e., iron, copper, tin, and lead—are produced in relatively large quantities. Together with precious metals (i.e., gold and silver), they still form the basis of industrial demand today.

Over time, the increasing use of modern production techniques and the widespread application of advanced technologies have increased the use of (and dependency on) other "minor" metals and metalloids. The demand for these minor metals and metalloids is likely to soar exponentially because they have specific properties that make them indispensable for the functioning of digital technologies and for building renewable energy solutions.

In general circumstances, mining companies tend to focus on the production of the most profitable commodities, leaving behind those that have a smaller market share, lesser value, are more difficult to extract or process (Mudd *et al.*, 2016), or may need additional investments for environmental reasons.

"Minor" metals are usually found in low concentrations (less than 0.1%) (Zepf *et al.*, 2014). In that respect, these metals rarely form economically viable deposits by themselves. They instead occur in interstices of "major" metal ores with which they share similar physical and chemical properties (Nassar *et al.*, 2015). These minor metals (also known as "companion metals") are thus mostly extracted as **co-products** or **by-products** of main mining operations that recover major metals (also called "host metals").

BOX 3. UNDERSTANDING THE DIFFERENCE BETWEEN CO-PRODUCTS AND BY-PRODUCTS

The production of co-products and by-products may help to maintain the profitability of a mining operation. The decision to produce a companion metal as a co-product or by-product depends on its concentration in the ore (its grade), its value, and the ease of building an adequate processing line.

It is important to understand the difference between co-products and by-products:

On the one hand, the term **co-products** refers to two or more metals that are produced jointly and whose economic mining values are of a similar order of magnitude, based on a combination of grade and price. Each co-product has an influence on mining decisions at the mine-site level and can justify specific investments.

On the other hand, **by-products** have a value that is generally too low to have an impact on mining decisions (such as extension of the life of the mine, specific infrastructures, or redefinition of the ore body itself).

Co-production and by-production present their own specific technical and economic challenges. These are summarized in the tables below.

Co-Production happens when **significant additional** investment is needed to mine and process the companion metal (Nieto & Zhang, 2013).	**By-production** occurs when there is **no or little additional** investment is needed to mine and process the companion metal (Nieto & Zhang, 2013).
Bidirectional relationship between **co-products**: Changes in price and/or demand for one metal can have significant effects on the other co-product and vice versa.	**Unidirectional relationship** between major metal and **by-product**: Changes in price and/or demand for the major metal can have a significant impact on the by-product, but any market change for the by-product does not affect the major metal.
An example of **co-production** is the lead–zinc (Pb–Zn) relationship. Often, lead and zinc are produced as co-products, resulting in most lead mines being also zinc mines and vice versa. If the market for one of these co-products is highly affected, such as through a ban on lead due to the risks associated with its neurotoxic characteristics, lead–zinc mines would not be able to continue to operate at a profit. This would result in a massive drop in zinc production and a surge in prices as zinc demand would remain constant and supply would be constrained (Frenzel *et al.*, 2017).	An example of **by-production** is tellurium (Te), which is essential for the production of photovoltaic cells and thermoelectric devices. It is a by-product of copper extraction and refining. More precisely, more than 90% of tellurium production comes from anode sludges produced by the refining of copper, after initial concentration and copper extraction of the ore has been performed (Rietveld *et al.*, 2019). In this situation, market demand for tellurium does not affect copper production and processing capacities, whereas the copper market has a direct influence on the amount of tellurium being made available.

Furthermore, co-production and by-production have significant implications from a **reporting and accounting** point of view. In the case of gold, in 2018, the World Gold Council recommended the following (World Gold Council, 2018):

Co-products should be **reported as sales**, as they improve the overall revenue of the operation. Costs are attributed to the production of each metal relative to its contribution to revenues.	**By-products** should be considered as a **reduction of the cost of sales**. It implies that revenues received from their sales are **deducted** from operating costs before calculating the cash cost for the primary metal.
For gold mines, if the secondary production represents **more than 20% of the overall production value**, it can be considered a **co-product** (Fulp, 2015).	If the **secondary production value falls below 20%** it is only a **by-product** (Fulp 2015).

3.0 Understanding Metal “Companionality”: A glance at the metal wheel

“Companionality” is the degree to which a metal is obtained—sometimes entirely—as a co-product or a by-product of a host metal during mining production (Nassar *et al.*, 2015). Companion metals tend to be associated with host elements with which they share similar physical and chemical properties.

Many minor elements are produced **only** as co-products or by-products of mining exploitation of one or two specific host metals. For example, 98% of current cobalt production comes as by-production from copper (60%) and nickel (38%) mines (Cobalt Institute, 2022). Gallium comes exclusively from aluminum (95%) and zinc (5%) mining operations (Bureau de Recherches Géologiques et Minières, 2016).

BOX 4. HOW TO READ THE METAL WHEEL?

The metal wheel was created by Nassar *et al.* in 2015. It is a visual simplification of metals production. The intention is to illustrate the relationships among elements with similar properties. It is understood that mineral deposits across the world show a wide degree of variability in their mineral content and associations based on their type and origin.

In the **centre circle**, the main host elements are displayed. These are the metals that are mostly mined and produced for themselves. There are 10 minerals in this category: aluminum, titanium, iron, nickel, copper, zinc, lead, tin, platinum, and gold.

Each **radiant** shows the companion elements statistically associated with the host element in mines.

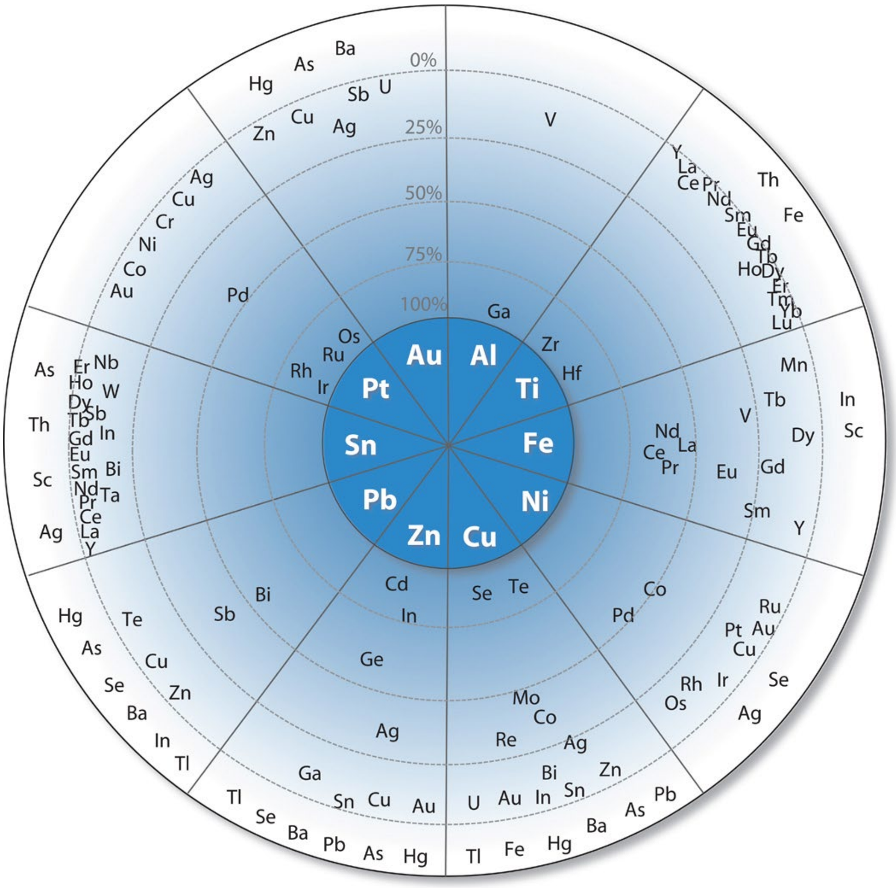
The **percentage** on the axis represents the average proportion of the companion element produced as by-production of the related host element. The darker the blue, the higher the proportion of the global production of the companion comes from the host element mines.

Companions that are on the white outer circle are those elements produced as by-products of the host elements in the centre of the wheel but whose percentage of companionality has not been established due to a lack of data.

These percentages are based on 2008 production data and illustrate a global average that does not consider deposit specificities, especially their metallurgical nature (oxide or sulphide).

Figure 3 illustrates metal companionality, that is, which minor metals are associated with ore deposits of major/host metals.

FIGURE 3. The metal wheel or metal companionality



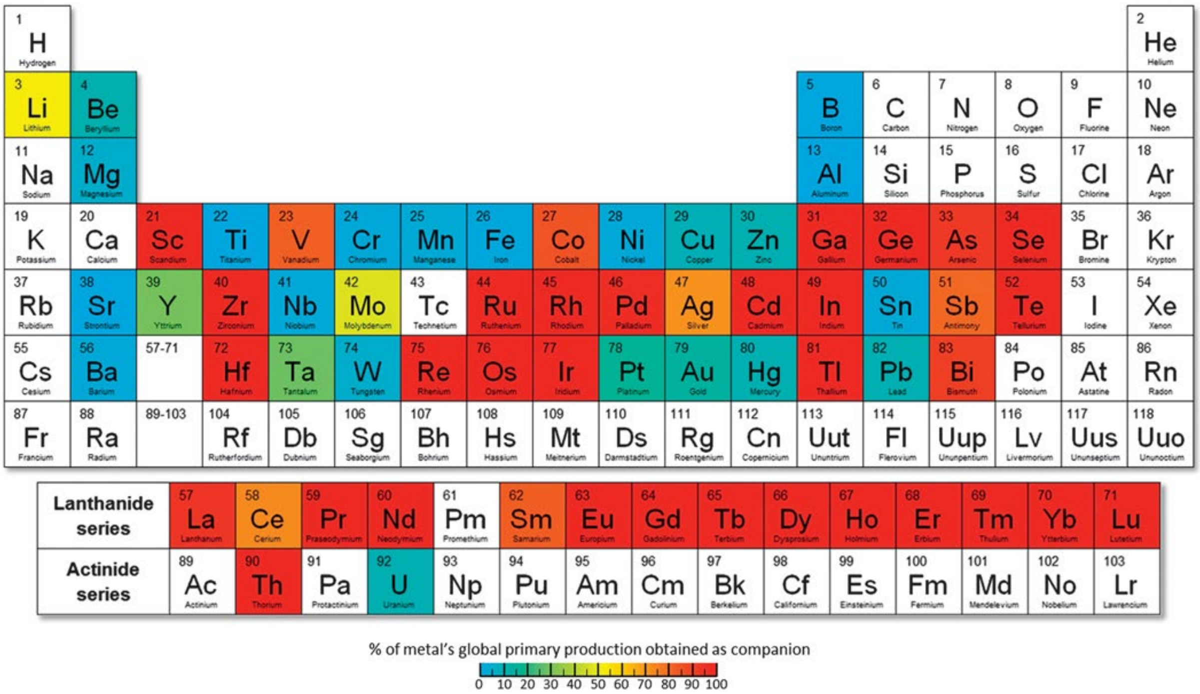
Source: Nassar et al., 2015.

Among metals that are considered critical[3] for the energy transition and for digital technologies, more than 60% are produced as co-products or by-products, as highlighted in Figure 4. This has significant implications because even if they are deemed strategic or critical from a policy and political perspective, rising demand is likely to result in problematic supply responses, as they may not be directly extracted for themselves.

As Figure 4 shows, the problematic supplies of co-products and by-products affect quite a significant number of metals to varying degrees. The bluer the element, the more it is mined for itself (i.e., it is a host or major metal). Iron, for example, is mostly mined as a major metal worldwide. However, as we move toward the red colour, the more the metal is mined as a co-product or by-product of a major metal operation. This is the case for cobalt, for example, which is largely a co-product or by-product of nickel and copper mines. Elements in white are those for which no companionality degree has been determined.

3 Many of these metals have been identified as critical by the European Commission and countries such as Australia, Canada, the United Kingdom, and the United States.

FIGURE 4. The periodic table of companionality on a global basis for 2008



Source: Nassar et al., 2015.

Because companion metals can only be mined alongside their host metals, this raises key questions about their availability, their accessibility, the material flow (i.e., the logistics chains from raw production to the end user), and their use in downstream industries.

4.0 Risks and Challenges Associated With Metal Companionality

4.1 Economic Considerations

4.1.1 Supply Risks

Trends in market demand for metals produced together can sometimes be correlated, as is currently the case for cobalt, a co-product of nickel and copper. In that instance, higher production of the host metals will also drive up the supply of co-produced metals.

But this is not always the case. Sometimes, there may be a fall in demand for the primary metal, while at the same time demand for the co-product or by-product rises. This is the case for lead and bismuth (a metal considered critical by the EU, the United States, and the United Kingdom, for example). Bismuth is used in the pharmaceutical industry and as an environmentally safer substitute for lead in the alloys used in turbine blades and TV and plasma displays, among other uses (Deady *et al.*, 2022).

In any case, future needs, driven by renewable energy infrastructure demand and digital technologies, may impact the demand for specific metals, as forecasts by the IEA suggest. However, markets, driven by rapidly evolving technologies, are often dynamic and volatile, which implies that in the future, there is no certainty that demand for specific metals will continue to grow at the same pace.

The supply of metals should not be considered in isolation. As mentioned, the economic viability of mining operations is often driven by the economic viability of "host" mining operations. Companion metals are not mined for themselves but rather as co-products or by-products of host metals, and decisions on whether to process them or not are often driven by factors such as:

1. The level of interest of the mining companies in producing only the main metals (or not).
2. The concentration of the minor metals: If it is considered too low for a cost-efficient economic recovery, they will not be processed.

3. The metallurgical process or the technology to separate such elements may not be developed enough for a specific type of ore.
4. Licensing and permitting requirements may hamper production: For instance, (i) the mining permit may not allow for any other production than the major metal for which the mining licence has been granted; (ii) authorization to process a "new" metal may require a new round of negotiations with the government; or (iii) extension of an existing licence may be granted on the condition that mining companies conduct new or supplementary environmental impact assessments, which may be costly and time consuming. [4]

The production and hence the availability of supply of companion elements, is totally dependent on the economic sustainability of the host metal extraction processes. As a result, companion elements have been—and still are—often discarded and disposed of within waste rocks and tailings at each stage of the concentration process.

Given the nature of the mining sector, the supply of metals is generally quite inelastic in the short term but tends to be more elastic over time as production comes on stream. The peculiarities of companion metals, however, tend to accentuate this issue, as their supply may not necessarily respond to market demand, even in the medium to longer term, but rather on the conditions mentioned above. The production of co-products and by-products is complex and seems to have a higher inelasticity of supply because it depends on whether the mining project, at a particular point in time, finds it technically and/or economically feasible to mine them.

Even co-products that jointly determine the production decisions regarding given metals remain highly dependent on the supply of the host metal, demand for which sometimes follows its own specific market dynamics.

For by-products, often considered as lesser important, higher prices may not be sufficient to trigger a higher production decision of the metal. These metals tend to have a higher inelasticity of supply.

Failing to consider these supply risks can hinder the pace of deployment of the energy transition and the digital transformation technologies. Not yet well understood and still unaddressed, slow supply responses will have a significant impact on global downstream value chains, putting whole industrial sectors at risk, including workers whose job security can be affected.

4 Although many jurisdictions allow the extension of the mining permit to other products, it requires a new negotiation between the mining company and the authorities. Such extensions are usually granted under the same conditions as the initial permit as is is the case in countries such as Senegal (Article 25 of the mining code (République du Sénégal, 2016) or the Republic of Congo (Article 34 of the mining code) (République du Congo, 2005). This could potentially represent an additional administrative and financial burden to companies if the cost to extract the by-product is only just covered by the additional expected revenue.

4.1.2 High Price Volatility

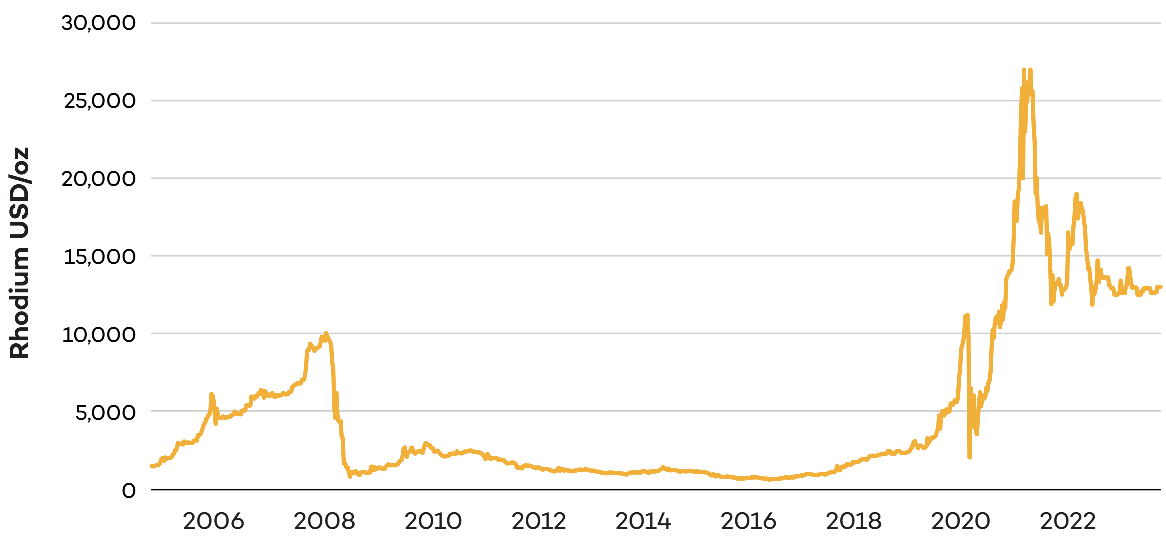
It is not uncommon for co-products and by-products to be subject to more price volatility than the host metals. Indeed, over the last 50 years, by-products had, on average, 50% higher annual price volatility than major metals (Redlinger & Eggert, 2016).

Rhodium, for example, which is a by-product of platinum and palladium, is predominantly mined in South Africa (80% of world production in 2018) and Russia (12% of world production in 2018) (United States Geological Survey, 2021). Its primary application is in catalytic converters (85% of rhodium production) (United States Geological Survey, 2021) where it is utilized to reduce harmful polluting gases emitted from vehicles.

As illustrated in Figure 5, rhodium was traded at USD 11,000/oz at the end of 2022, down 42% from its peak of USD 19,000/oz in March 2022 and down 60% from its highest price of USD 27,000/oz in April 2021, but up 320% from USD 3,500/oz in March 2020.

Another illustration from 15 years ago was when the car industry, the biggest consumer of rhodium, was hit by the 2008 crisis. Rhodium prices fell more than 90% in a few months, from USD 10,000/oz to less than USD 1,000/oz.

FIGURE 5. Evolution of rhodium prices in USD/oz from April 2005 to January 2023



Source: Kitco.com, 2023.

Uncertain market conditions for some minor metals might deter mining companies from venturing into the production of minor metals, further accentuating the supply risks and price fluctuations.

Volatility in price is also a challenge for governments, as it prevents them from adequately budgeting revenues expected from the mining sector, thus limiting their ability to properly plan public spending.

Ultimately, high fluctuations in commodity prices have a negative impact on the social fabric, and in particular on workers, who are at risk of being laid off during the bust part of the boom–bust cycle. Managing such cycles better would result in tangible benefits for mineworkers, their families, and their communities.

4.1.3 Risks of Losing Metals of Strategic Importance (Such as Critical Minerals)

Considering the growing need for a wide range of metals, disposing of metals in waste dumps and tailing storage facilities without processing them can represent a tragic loss of value. As the supply gap for minerals considered critical for the energy transition and for digital technologies grows, research is ongoing to try to limit such loss and recover as much of them as possible. This would require necessary metallurgical developments that would allow for a process as simple as possible that would maximize the recovery of companion metals.

Not processing minor metals represents a potential value erosion for mining operations and for governments. For tax authorities of host country governments, in particular, it reduces the revenue that can be collected and redistributed, including to host communities.

4.1.4 Risks of Reserves and Resources Under-reporting

Current estimates of metal reserves and resources are largely imperfect, in part because there is no universally agreed guidance or definitions of primary products, co-products, or by-products in mineral resource reporting codes (Mudd *et al.*, 2016). Different countries use different methods and have different ways of aggregating and disclosing data, which result in variations in metal reserve and resource estimates.

These variations are even more pronounced for companion metals, which are often perceived as having less material value for recovery by mining operations, and therefore remain overlooked and under-reported. Even when the valorization of companion metals is considered in the feasibility study of a mining project, their resource estimates are often hidden and presented as a main metal equivalent.

This results in a lack of reliable data on resource estimates and on the quantity and quality of minerals available and hence, the extent to which they can feasibly be mined and processed at scale. The lack of sufficient and reliable data exacerbates uncertainties in the market for the minerals that are in particularly high demand for the energy transition and digital transformation. It further hampers the ability to anticipate and address risks around security of supply and where and how to focus efforts and priorities for more research and exploration. Better and more transparent reporting can thus have a significant role in mitigating price volatility.

For producing countries, the uncertainty in relation to the quantity and diversity of their minerals and metals endowment remove their capacity to properly design and lead an effective national mining and industrial strategy.

For mining companies, the lack of proper data is a missing opportunity to diversify their portfolio and reconsider mining metals that are otherwise classified as low-priority or unprofitable assets.

BOX 5. WHAT ARE MINERAL RESOURCES AND RESERVES?

Mineral resources and reserves are accumulations of a mining commodity that can be extracted at a profit under current technical and economical conditions. Having for a large part an economical component, any fluctuation in commodity price affects the quantity of resources and reserves available.

The terms "resources" and "reserves," in current usage, are reporting terms that are mandatory for most publicly listed mining companies. They are defined within standard disclosure codes, such as the Joint Ore Reserves Committee (JORC)[5] (Australia and New Zealand), South African Mineral Reporting Codes (SAMREC)[6] (South Africa), and National Instrument (Ni) 43-101[7] (Canada), for example, that have been developed by stock exchanges to help investors compare mining exploration projects and limit false or misleading reporting. They set minimum standards, guidelines, and recommendations for public reporting of mineral property assets. They also serve as a framework for resource and reserve classification based on geological knowledge, metallurgical recovery amenability, and the economic feasibility of mineral properties. They are based on the notion of "competent person" (JORC, SAMREC) or "qualified person" (CIM Ni 43-101), that is, a technical expert recognized by their peers who is required to sign off the report disclosing the results.

A Mineral Resource is the part of the mineral deposit for which there is enough technical confidence in the geological model to expect a future mining exploitation. Resources can usually be separated into three different categories, ordered according to increasing geological confidence:

- Inferred resources
- Indicated resources
- Measured resources.

A Mineral Reserve (Ni 43-101, SAMREC) or **Ore Reserve** (JORC) represents the economically mineable part of a measured and indicated mineral resource. Only a pre-feasibility or feasibility study for a mining project can provide enough additional information to support the upgrade of resources to reserves. Reserves are usually classified into two categories ordered according to increasing geological confidence in the mineral resources:

- Probable reserves: They are derived from indicated and measured resources.
- Proven reserves: They can only be derived from measured resources.

5 The JORC code is the Australasian code for reporting of exploration results, mineral resources and ore reserves. It is mandatory for companies listed in a stock exchange in Australia and New Zealand.

6 SAMREC, or the South African code for the reporting of exploration results, mineral resources, and mineral reserves, sets minimum standards, recommendations, and guidelines for disclosure of mineral information.

7 Ni 43-101 is the Canadian standard of disclosure for mineral projects. It is mandatory for any release of information related to mineral property for companies listed on any stock exchange in Canada.

4.1.5 Risks of Illicit Material Flows

During the concentration process, whereby raw materials undergo chemical and physical processes to be upgraded into higher-grade concentrates, many companion metals remain alongside the host metals, given that they share similar properties. Concentrates of the host metals can then be sold to smelters and refiners to be further separated and processed into sellable metals. What remains is considered to be impurities with no value or for which the smelter can charge penalties for.

In many producing countries, concentrates that are exported without further transformation are not systematically tested by governments for elements other than the main metals and major recognized impurities. In fact, when minor metals are not part of the portfolio of mining companies, they are rarely declared as “extractable” minerals and therefore remain unreported. While strong guidelines exist (Readhead, 2018) for governments of producing countries to assess the grade and the volume of the commodity exported, no assay and protocol would identify any element if the exported materials are not tested for specific elements.

This is a major challenge, as governments are unable to estimate the volume and the value of all minerals that are sold or exported. Materials shipped abroad without proper declaration and/or reporting represent a high risk of **material flight** or even **illicit material flows.** As a consequence, governments are unable to claim the right share of revenues.

With 60% of critical minerals estimated to come from minor metals, and given the exponential demand expected in the future, the potential material flight or illicit material flows represent a significant financial risk and missed revenue opportunity for governments and companies alike.

4.2 Environmental Risks

Releasing companion metals from mining or processing operations in waste dumps or in tailing storage facilities also raises underlying environmental issues, as some of these elements are toxic (such as lead or mercury, which are highly neurotoxic) and have been made more mobile as a consequence of the mining and extraction process.

Closed and abandoned tailings represent one of the most important sources of heavy metal pollution in places where mining activities occur or have occurred. Further leaching from rainwater can disseminate downstream and precipitate the heavy metals that remain in closed tailings storage facilities (Wang *et al.*, 2019). This presents a significant threat to the environment, to local communities, and to mine workers. For the mining industry, this is specifically acute since employers have the duty to protect their workers and to support the health and safety of their employees (International Labour Organization, 2003, 2005).

Any extension of the quantity of companion metals recovered would help mitigate this major risk. The use of new and better processing techniques that align with higher environmental standards represents an opportunity to address those negative impacts and environmental legacy issues.

Some undesirable companion elements can even prevent a deposit from being mined. The Kvanefjeld rare earths project in Greenland, which is estimated to hold over 1 billion tonnes of mineral resources (Greenland Minerals and Energy, 2015), is currently halted because of uranium by-production. The exploitation licence has been rejected by the authorities based on a new law passed in 2021 that bans exploration and production for any mining project for which the concentration of uranium exceeds the threshold of 100 ppm (part per million or 0.0001%) (Jamasmie, 2021).

4.3 Recycling Challenges

In theory, metal (being atoms) can be 100% recycled compared to compounds such as plastics, for example, whose molecular chains are degradable by heat, ultraviolet light, or over time. In practice, however, metals companionality brings additional challenges for recycling.

Metals are usually highly diluted in manufactured objects (Verhoef, 2004), and this is particularly acute for minor metals that are used in very small quantities. In that regard, metallurgy of recycling has a level of complexity similar to that of mining metallurgical processes. However, unlike mining processing, where metals associated occur naturally, in manufactured objects, the metals contained and associated therein respond to technological properties. Minor metals from manufactured objects are therefore more difficult to recycle because their associations are not natural. In that regard, the metallurgical knowledge developed and used to handle naturally occurring ores might not be adaptable or relevant to the secondary processing of "artificial ores."

5.0 How Understanding Companionality Can Help Identify New Sources of Metals

Current projections on metal demand from the development of energy technologies point to a significant supply gap in the coming decade (IEA, 2021). While drivers of demand are relatively clear, we struggle to estimate where the minerals will come from, at what pace they will be produced, and how some minor metals will be recovered, given the fact that technically they cannot be mined for themselves. That said, a more granular understanding of how metals are mined and associated together can provide a new lens for policy-makers to put in place the necessary policy and regulatory instruments, invest in research and development, provide adequate support for new techniques of processing, and facilitate access to new sources of metals. It also provides a platform to engage with mining companies and other industrial actors down the supply chains to leverage opportunities to help bridge the supply gap. This section unpacks some of the key opportunities that can be leveraged with a better understanding of metal companionality.

5.1 Opportunities to Get Higher Value From Metal Production

The growing demand for minerals that are critical for the energy transition and digital technologies brings a new lens to the economics of companion metals.

The processing of companion metals represents an opportunity to raise the profitability of mining operations, notably by making better use of the capital invested and the intensive work already performed, from exploration to extraction and comminution.

This is a boon for producing countries as well, as it provides new avenues to benefit from their sub-soil assets and develop value-added activities—and hence participate in global supply chains.

Co-production and by-production also represent an opportunity for producing countries to rethink their fiscal regime to introduce more flexibility for some types of minerals. One example is the introduction of variable royalty rates, which are more progressive than fixed rates (IGF 2022). Charging variable royalties rates on host metals can, however, be difficult because costs and prices typically rise and fall in tandem. But applying such variable royalty to minor metals limits any risk to the profitability of the mining operation in cases in which by-production alone does not have enough value to influence investment decisions. As a result, this could provide additional revenue stream to resource-rich countries without deterring investment in the mining sector. However, there needs to be some flexibility in applying variable rates, in particular in the case of co-produced metals, as they could rival or even overtake host metal production.

BOX 6. NEW BY-PRODUCTS FROM A TIN MINE

The Uis mine in Namibia is operated by Andrada Mining (previously AfriTin Minerals). It entered production in 2019 to produce a tin (Sn) concentrate. Metallurgical tests have been successful in extracting lithium and tantalum as by-products. Construction of a pilot plant to produce battery-grade lithium hydroxide and a tantalum separation circuit to produce tantalum oxide concentrate will soon be initiated (AfriTin Mining Ltd, 2022). Interestingly, depending on the relative price evolutions of tin and lithium (and should the relative concentrations in the ore deposit allow it), lithium could replace tin as the main product in this specific mine.

5.2 Waste Dumps and Tailing Storage Facilities as Potential Sources of Critical Minerals

For the reasons mentioned above, most tailing storage facilities, especially those that are closed, host significant amounts of companion metals that have been mined but discarded as part of the recovery process of the host element. Even if exploitation of such minor elements was not studied as part of the initial feasibility study of mining projects (or has been studied but not deemed economically viable at the time of the study), there is scope, with the rising demand for critical minerals associated with changes in overall economic conditions and technological breakthroughs, to mine those tailings to recoup minor metals.

This would require new geological assessments of resources and reserves contained in such tailings and has significant potential to change the status of such materials from wastes to (new) ore deposits that can be re-exploited.

BOX 7. THE NEW ALCHEMY: TRANSFORMING WASTE INTO WHITE GOLD

The Boron mine in California is a 90-year-old borates mine operated by Rio Tinto that has produced a significant quantity of tailings over time. To assess their remaining potential mineral value, these tailings have been tested for gold and other potential by-products. Results revealed lithium at concentrations that could justify re-exploitation. A small-scale trial was successfully initiated in 2019 to prove the technical viability of the project. A feasibility study is currently in progress to build a processing plant with an initial capacity of 5,000 tonnes per year, enough to supply lithium for 70,000 electric vehicles (Rio Tinto, 2021).

Furthermore, the value contained in these closed tailing storage facilities that could justify an intervention brings an important additionality. It offers the unique opportunity to redress installations that are becoming a threat to the environment and communities due to outdated designs, constructions, and norms in the context of climate change. However, reprocessing tailings should be highly controlled and monitored to avoid disastrous tailings dam breaches, such as the September 2022 event in Jagersfontein, South Africa (Eligon, 2022).

The reprocessing of tailings provides a significant revenue opportunity for host countries. It can also create—and help develop—a whole new sector, with associated new and different employment opportunities. These new jobs may require new specific competencies that will align with the improvements to the country skills base.

While, in principle, reprocessing tailings is a seductive source of critical minerals, there are several regulatory obstacles that need to be addressed to make the business case for investors. For instance, lack of clarity on tailings ownership—especially in the case of abandoned and orphaned mines—and hence, on their safety, is a clear obstacle to any potential investor. Furthermore, land rights issues, permitting costs and delays, environmental clearance, access to technology (especially for medium-sized companies), and financing of tailings' reprocessing operations are often considerable bottlenecks that need to be addressed to attract investors.

Governments could unlock the potential to transform what is considered an environmental liability into a resource-recovery opportunity for critical minerals. Achieving this will require a strengthening of the regulatory framework, the providing of incentives, and greater consistency across different fields of public policy to ensure the sustainability of practices. Also, to make the business case for investors (and considering the externalities that may be associated with reprocessing activities), appropriate and comprehensive investment schemes, such as dedicated schemes to mining wastes valorization, will need to be designed, taking into account their integration into licensing regimes from the outset, and appropriately funded.

5.3 Opportunities to Align Mining Production With National Development Strategy

The quest for an increasingly higher volume and different types of minerals and metals to power the technologies needed for a sustainable future—as well as strategies to ensure security of supply—is pressuring a growing number of mineral-producing countries to ramp up their mineral production and to enter into long-term supply agreements.

These dynamics are placing producing countries in a position of strength and therefore give them an opportunity to rethink their strategic positioning, both in terms of national development strategies and with global partners. From a national development perspective, a good handling of the mining production mix is critical to fostering industrial development and value addition, and stimulating investments in economic sectors that can drive a climate-smart future. From a global perspective, this offers a unique occasion for producing countries to strengthen their position in global supply chains and secure fairer and more equitable deals with investors.

To make these opportunities materialize, it will be important to review regulatory processes to grant licences or permits when data exist regarding metals' companionality. While the permitting system should not hinder mining companies from processing minor metals when this processing is economically feasible, governments should be able to reassess the terms and conditions of the licence or permit in case of "material change."[8] In addition, governments should be informed about the level of processing of companion metals even if they are not processed and should have clear transparency and reporting requirements, including regarding the systematic submission of detailed geological data and on the classification of metals as by- or co-products. This is important because some minor metals can be recategorized to change their classification from by-products to co-products if the production value becomes significant at a given point in time.

From a planning perspective, understanding natural metal associations and having a good database of metals companionality is essential for producing countries to identify which minerals are being mined and which may not yet be recovered, to then stimulate exploration or promote specific recovery from existing mines or mining projects.

8 Material change refer to a substantial change that has a significant effect on the overall business operation.

6.0 Conclusion

From exploration to mining, processing, and tailings reprocessing, understanding companionality is key to identifying innovative ways of addressing the looming supply gap in minerals needed for the energy transition. It thus adds a new tool to the mining sector toolbox.

The main takeaway of the notion of metal companionality is that metal extraction and the feasibility of supply cannot be considered in isolation. Furthermore, the production of a large number of metals is interconnected and therefore requires a comprehensive understanding of how market dynamics for these metals (individually and collectively) work and how they might affect the ability of the mining industry to supply metals that are in high demand but not necessarily in high supply.

To encourage mining companies to invest in minor metals that are considered of lesser interest (and hence treated as by-products) but otherwise critical for a wide range of industrial applications, governments could consider providing specific incentive schemes to support investment in the recovery of companion metals alongside host metals. In return, governments could mandate exploration companies to conduct and disclose multi-element analysis of soil samples to ensure all elements or associated minerals are considered.

A significant amount of metals are mined, but not all of them are processed, for the reasons highlighted in this paper. This means that tailings and waste dumps, for example, are full of elements that at a given point in time might not have been considered important but may become extractible considering current supply constraints. To mitigate risks and take advantage of opportunities, fundamental research on metallogeny, as well as applied research on metallurgy processes, should be encouraged.

From a policy perspective, there are important economic and environmental risks that need to be addressed to make reprocessing of tailings environmentally safe. However—and importantly—this also offers huge opportunities, as technological development and plans to move to a greener future bring a greater focus on minor metals of significant importance to industrial needs. It is also an opportunity for mining companies to enhance the value of their operations and optimize the supply of critical minerals.

To facilitate exploration and investments, synergies and partnerships between public research bodies and mining companies, including at the regional level, should be promoted and developed. This would help identify innovative ways to process minor metals and valorize minerals and metals that are (or have been) mined but are considered to be waste by mining operations.

The buoyancy in the market for metals—notably the high price volatility, global strategies to secure access to critical minerals, and the proliferation of supply contracts directly between supply chain actors and mining companies—is intimately linked to the difficulty and slowness of the response of production supply to demands. Understanding metal companionality can help bridge the knowledge gap on how feasible it is to extract some of the minerals and in which types of ore bodies there is a greater possibility of finding them. It thus enables informed decisions when making plans about the use of those metals in industrial applications.

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