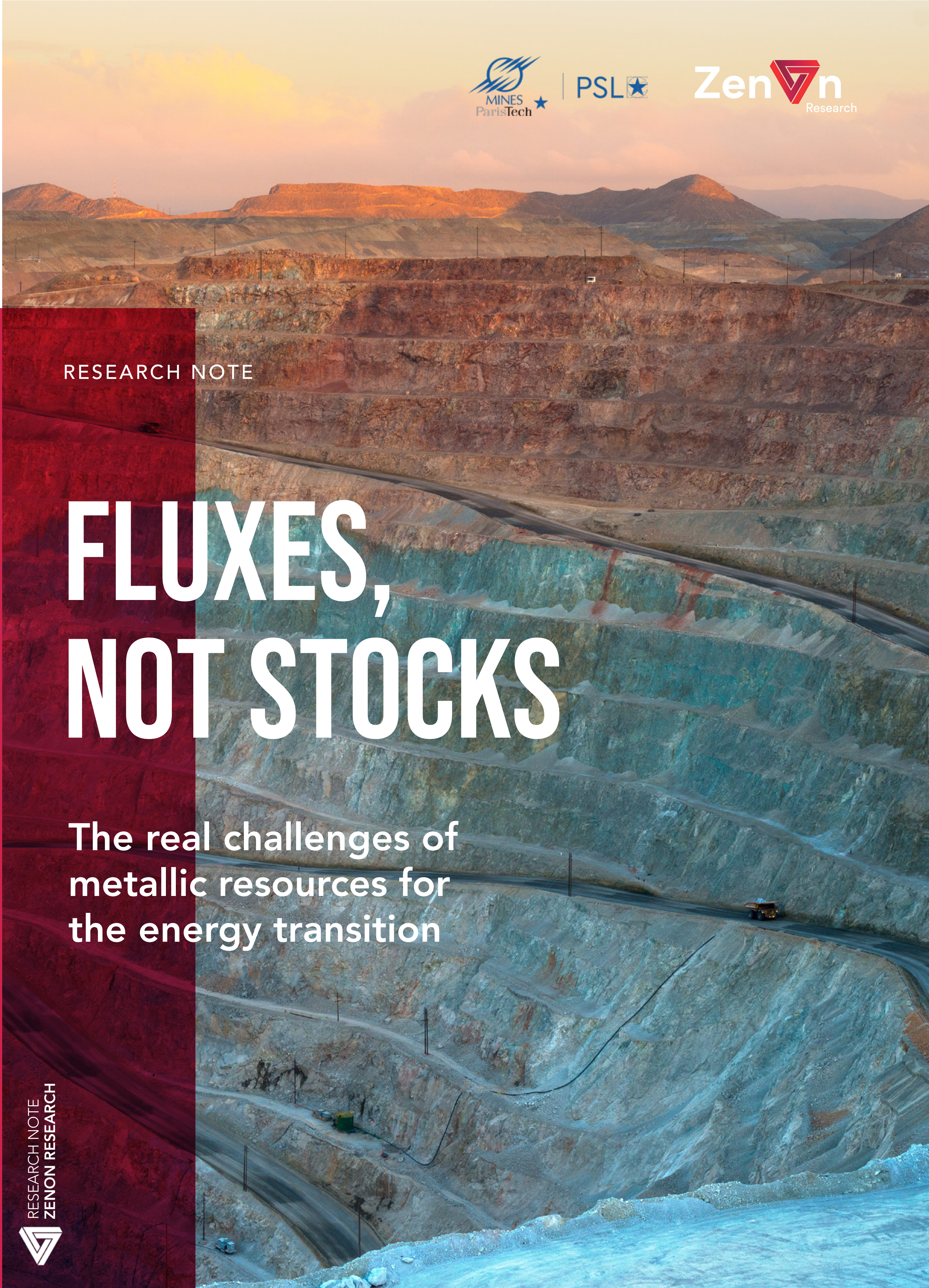


RESEARCH NOTE

FLUXES, NOT STOCKS

The real challenges of metallic resources for the energy transition

RESEARCH NOTE
ZENON RESEARCH

Key Takeaways

To this day, the demand for metals has kept increasing. The energy transition necessary to meet climate objectives will add to that demand during the upcoming decades, for low-carbon energy technologies require larger metal quantities than their fossil-fuel based counterparts. This frequently raises concerns over the actual capacity of geological stocks to meet demand at scale, which we investigate in the present analysis.

Mining of metals

- Ores are parts of the Earth's crust that show particularly high mineral concentrations, allowing to extract metals in a technically and economically viable way. Some metals (aluminium, iron…) are orders of magnitude more abundant than others (precious metals). Rare earth elements, a group of metals that share specific properties, should not be mistaken with rare metals in a geological sense, some rare earths being almost as common as copper.

- The heterogeneous ore repartition and potentially conflicting national interests result in a geopolitically complex mining landscape. China notably is a main actor of the sector, controlling most rare earth extraction chains and large shares of the refining processes for most metals required for the energy transition.

Will we run out of metals?

- Resources are the part of a geological stock whose exploitation is deemed potentially feasible – reserves are the part of it that can be exploited under current standards. Those are dynamic entities, which are not only defined in geological terms but also vary with the socio-economic context.

- Resource depletion is difficult to assess. Resources are only known from statistical estimates. Globally decreasing mined ore concentrations can result from a variety of factors, e.g., technical enhancements. Peak models are often criticized for being too simplistic. The ratio of reserves to production, or "depletion time", is confusing on the long term because of the dynamic nature of resources and should be used as a short-term indicator solely.

- The availability of metal commodities is a concern that goes way beyond their geological abundance only: it is mainly a problem of supply that should be assessed in a comprehensive way, by considering a variety of socioeconomic indicators – using, for instance, the concept of criticality.

The future supply of metals

- Energy demand scenarios differ a lot regarding both the total energy demand considered by 2050 and the shares of individual technologies in the global mix. This results in a variety of estimates for the metal demand. However, all scenarios highlight a significant increase in demand for the energy sector – with, for some metals, a likely increased share of energy uses in the total demand.

- Vulnerabilities along the supply chain, that are likely to be exacerbated by the scale of demand, might lead to supply shortages. Such vulnerabilities include more complicated mining and refining processes with increasing energy expenditure, long development times for mining projects, geopolitical vagaries, or increased water stress due to climate change.

- Reducing dependency on primary metals extraction can both lessen vulnerabilities and reduce some negative (e.g., environmental) impacts of the mining industry. However, strategies to reduce demand, such as material substitution or gains in material efficiency, come with a number of significant limitations. High recycling rates can be very energy-intensive, and there are structural limitations to the quantities of materials available for recycling at a given time (locked-in in infrastructures). The potential impacts of behavioural changes and sufficiency strategies should also be considered in that regard.

- The relation between metal demand and GDP is key to understanding the dynamics of demand increase: both factors are strongly coupled in developing countries, which are expected to be the main drivers of demand growth in the upcoming years. Quantitative research on such topics shall be further developed.

Ce qu'il faut retenir

Historiquement, la demande mondiale en métaux n'a cessé de croître. La transition énergétique nécessaire à la réalisation des objectifs climatiques va contribuer à ce phénomène durant les prochaines décennies ; en effet, les technologies de production d'énergie bas carbone requièrent plus de métaux que leurs homologues fossiles, tant en quantité qu'en termes de diversité. Cela génère souvent des inquiétudes quant à la capacité des stocks terrestres à satisfaire la demande à venir, sujet décrypté dans le présent rapport.

L'exploitation minière des métaux

- Les gisements à partir desquels sont tirés les métaux sont des portions de la croûte terrestre particulièrement concentrées en minerais, permettant la viabilité technique et économique de l'extraction. Certains métaux tels que l'aluminium ou le fer sont considérablement (plusieurs ordres de grandeur) plus abondants que d'autres (comme les métaux précieux par ex.). Les terres rares, un groupe de métaux aux propriétés particulières, sont à distinguer des métaux rares au sens géologique – certaines sont quasiment aussi abondantes que le cuivre.

- La répartition hétérogène des gisements combinée à des intérêts stratégiques divers expliquent la complexité géopolitique du paysage minier. La Chine est un acteur majeur du secteur, contrôlant notamment une grande partie de l'extraction des terres rares et du raffinage d'un grand nombre de métaux nécessaires à la transition.

Court-on le risque d'épuiser les ressources métalliques ?

- Les ressources sont la partie des stocks géologiques dont l'exploitation est considérée comme potentiellement faisable – les réserves, la partie des ressources exploitables selon les standards actuels. Ce sont des entités dynamiques, qui ne sont pas seulement définies en termes géologiques, mais varient aussi selon le contexte socio-économique.

- L'épuisement des ressources est complexe à évaluer. Les quantités mondiales ne sont connues qu'à partir d'estimations statistiques. La baisse à l'échelle mondiale des concentrations de minerais exploités peut être due à de nombreux facteurs (progrès technique par ex.), les modèles de « pic » de production sont souvent considérés comme trop simplistes, tandis que le rapport entre réserves et production à un instant t ne donne d'indications pertinentes que sur le court terme, du fait de la nature changeante des ressources.

- La disponibilité des ressources métalliques est une question qui va au-delà de leur seule abondance géologique ; il s'agit principalement d'un problème de flux d'approvisionnement, qui se doit d'être évalué de manière systémique (notion de criticité), en considérant une variété d'indicateurs socio-économiques.

Futur de l’approvisionnement en métaux

- Les scénarios énergétiques présentent une grande variabilité, tant en ce qui concerne la demande mondiale en énergie pour 2050 qu’au niveau des parts relatives de chaque technologie dans le mix total. Cela se traduit par une forte diversité d’estimations des besoins en métaux, bien que tous les scénarios s’accordent sur le constat d’une demande fortement accrue, avec pour certains métaux une probable augmentation de la part du secteur énergétique dans la demande totale.

- Les chaînes d’approvisionnement présentent de nombreuses fragilités, qui seront amplifiées par la demande attendue, et qui pourraient conduire à des pénuries : augmentation de la complexité et des besoins énergétiques des activités minières, échelles de temps longues inhérentes au secteur, instabilités géopolitiques, pression accrue sur les ressources en eau due au changement climatique…

- Pour atténuer ces fragilités, et par la même occasion réduire les impacts négatifs (par ex., environnementaux) de l’industrie minière, il semble nécessaire de réduire la dépendance à l’extraction primaire de métaux. Cependant, la plupart des stratégies pour réduire la demande, telles que la substitution ou les gains en efficacité matérielle, présentent un certain nombre de limites. Des taux de recyclage élevés requièrent de grandes quantités d’énergie. Structurellement, les systèmes énergétiques immobilisent de grands volumes de matériaux avant d’atteindre leur fin de vie, rendant ceux-ci indisponibles au recyclage. Il est en outre important de ne pas négliger le potentiel des stratégies de sobriété et de la modification des comportements.

- Le lien entre demande en métaux et PIB est essentiel pour comprendre les dynamiques de hausse de la demande : ces deux grandeurs sont fortement couplées dans les pays en voie de développement, dont on peut attendre qu’ils seront moteurs de la demande dans les années à venir. Des analyses quantitatives sur ce sujet de la consommation restent encore à développer.

FLUXES, NOT STOCKS

The real challenges of metallic resources for the energy transition

Low-carbon energy technologies require higher amounts of minerals per energy unit than their fossil fuel-based counterparts[1]. A global-scale energy transition in line with the climate objectives will therefore be particularly material-intensive, which, by shifting our extraction dependency from hydrocarbons to minerals, raises the question of resources[2].

The case of metals in particular has been widely discussed. Since their first uses in industrial-scale applications, the consumption of metals has only increased over the years, particularly during the 'Great Acceleration' of human activities that started in the 1950s – about 90% of the historic copper production (Cu) was mined since then, with almost the half of it during the past 20 years only[3]. The last decades have also seen a drastic increase in the variety of metals used in technologies[4], which is also the case with low-carbon energy technologies (see Box 1).

Mineral commodities are available only in finite quantities in the Earth's crust. This raises concerns about the possibility of resource depletion in case demand exceeds the available quantities, be it short-term supply shortages or the definitive exhaustion of certain commodities. The transition to metal-intensive technologies is likely to add tensions to an already constrained market, which could significantly hamper the success of the global shift to low-carbon energies. Therefore, it is crucial to ask the following question: **Will metallic resources be sufficient for the energy transition?**

The present document focuses mainly on identifying the key challenges related to this question and putting them into perspective. The purpose is to provide the reader with a critical synthesis on the topic, rather than trying to formulate definitive answers to the question – which would be a vain attempt. It is thus intended to serve as a base to further analyses, later to be published, that will focus on more specific issues.

Mining of metals

The geology of metals

The observed distribution of mineral concentrations in the Earth's crust is highly heterogeneous. It results from complex physical and geological processes that occur over millions of years, such as plate tectonics and erosion[7]. The average concentration of minerals in the Earth's crust is too low for the metals to be extracted in a technically and

BOX 1

Which metals are needed for the energy transition?

The energy transition relies on a variety of technologies that come with specific requirements in terms of materials. Such technologies require a certain number of *base* or *industrial* metals, already commonly used in other industrial sectors. Steel, which requires the mining of **iron (Fe)**, is a major structural component of all energy infrastructures. Transmission lines in electric grids are composed of either **aluminium (Al)** or **copper (Cu)**. The latter is generally used in significant amounts in all power generation technologies. **Zinc (Zn)** is mainly required in wind turbines as an anti-corrosive coating. Further important base metals include **nickel (Ni)** and **manganese (Mn)**, for instance in some lithium-based battery chemistries. **Lithium (Li)** and **cobalt (Co)** are examples of *specialty* or *technology-critical* metals, that are more specific to a certain technology – here, certain Li-batteries – and comparatively extracted at a relatively small scale (see Box 3). Some **rare earth elements (REEs)** are used in permanent magnets for EVs and some wind turbines architectures (which currently represent around 20% of the installed capacity, mainly off-shore turbines). Thin-film photovoltaic (PV) technologies, still minor compared to crystalline silicon (c-Si) PV, are based on rare metals and metalloids such as **cadmium and tellurium (CdTe)**. Finally, *precious metals* are also needed for certain applications: **silver (Ag)** for contacts in c-Si PV panels, **platinum (Pt)** and **palladium (Pd)** in fuel cells.[5, 6]

economically viable way. The mining industry therefore relies on ore deposits, i.e., particular sediments and rocks which show mineral grades (concentrations) higher than a certain minimum threshold – the *cut-off grade*[8].

The different metals of the classification come in a variety of abundance levels. Aluminium (Al) and iron (Fe) are among the most common elements in the Earth's crust, with concentrations of about 8% and 3-4% respectively[9]. Their abundance and their interesting properties explain their wide use as industrial metals. Copper (Cu), another base metal, is several orders of magnitude rarer, its concentration in the lithosphere ranging from 10 to 50 parts per millions (ppm), similar to zinc (Zn), nickel (Ni) and some light rare earth elements (REEs). Precious metals are characterized by very low concentrations of the order of a part per billion (ppb) – such scarcity explaining their high market prices. The ratio between the average grade in exploitable ores and the natural abundance, called the *enrichment factor*, can be as high as 10,000 for precious metals such as platinum (Pt)[9].

In a given deposit, minerals often come in an intricate mix of diverse concentrations. A variety of metals are not mined for themselves, but as *by-products* of a *host metal* which is more common and/or shows a higher concentration in the considered ore[10]. For instance, most of the world's cobalt (Co) is obtained as a by-product of copper (Cu) or nickel (Ni), with only one major primary cobalt mine existing to date[5]. Some groups of metals, such as platinum-group metals (PGMs), because of their very similar chemical properties, are often found together in a given ore deposit, in varying individual proportions[11]. A significant number of metals necessary to the energy transition are mined as by-products, which can have significant implications to their supply security, particularly when geopolitical considerations come into play.

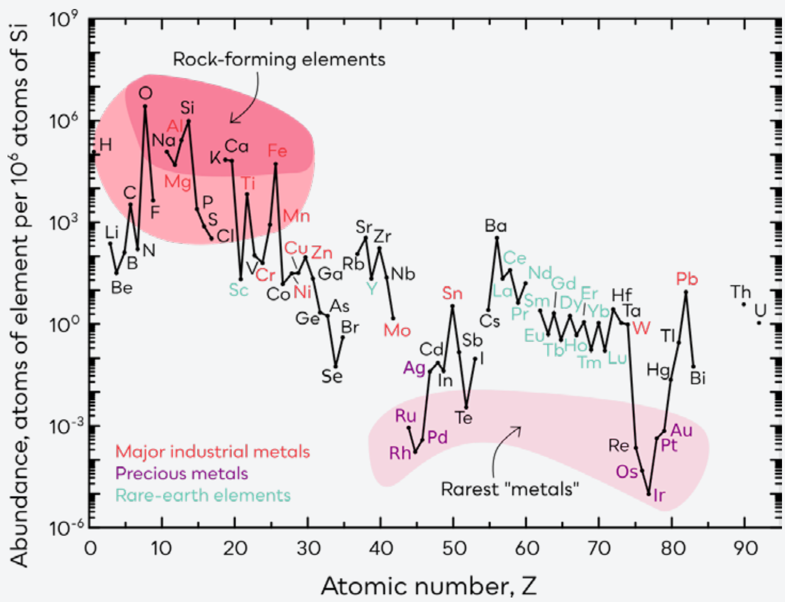


Figure 1: Relative abundance of elements in the Earth's crust. Adapted from USGS (https://pubs.usgs.gov/fs/2002/fs087-02/)

BOX 2

Are rare earths... rare?

Rare earth elements (REEs) are a group of 17 metals, comprising the 15 lanthanides, yttrium (Y) and scandium (Sc). They share similar chemical properties and are thus often found together in ore deposits, like PGMs. A common misconception, much due to their misleading name, is that REEs are geologically scarce. The reality is more nuanced. Some light REEs such as cerium (Ce) or neodymium (Nd) are found in proportions similar to copper (Cu), at 68 and 38 ppm respectively. Most REEs are four orders of magnitude more common in the Earth's crust than precious metals such as gold (Au) or platinum (Pt). Issues with REEs supply have more to do with geopolitical aspects than with their geological scarcity – in fact, their supply on the medium- and long-term is often considered less 'critical' than that of some major metals.[7, 12]

Geopolitics

The mining industry operates within a particularly complicated geopolitical context, with production and refining activities concentrated in a small number of countries that need to respond to an ever-increasing global demand (see figure 2). While the distribution of mines primarily results from the heterogeneous distribution of minerals, geology is not enough to fully explain the complexity of metals geopolitics, being intertwined with a variety of political and strategic considerations.

Lithium (Li) is a case in point. More than half of the global resources are found in the so-called 'lithium triangle', a region of the Andes with very rich salt flats which encompasses Bolivia, Argentina, and Chile[13]. Despite having the highest potential with about 21 million tons[14], Bolivia has remained reluctant to exploit its resources, for different reasons (competition with water uses, marked interest in developing a national battery industry rather than focusing on mining solely). As a consequence, although it is only the fourth country in terms of resources, Australia is currently the world's leader in Li extraction (from other kinds of deposits).

China is a major actor in the global metals industry, with particularly strong national policies and incentives towards mining in the wake of its Belt Road Initiative (BRI). It is notably the leader in REEs extraction, with 60% of the global production as of 2019. The particularity of China, however, lies in its dominance in the refining operations for most metals of interest: more than half of Li and Co, more than 40% of Ni and Cu, and as high as 87% of REEs are refined in China[5]. On top of that, Chinese foreign investment operations allow the country to control even greater shares of the market[2], for example through investments in Chilean and Australian Li mining companies[6].

Will we run out of metals?

The increasing demand for metals expected over the coming years to achieve the energy transition frequently raises concerns over the possible depletion of mineral deposits. Insufficient material supply could hamper the climate mitigation goals and have a number of implications also for non-energy uses.

The fear of running out of resources is not recent. Already back in 1798, Malthus was worried about the ability of agricultural resources to respond to exponential population increase[17]. Focusing on metals,

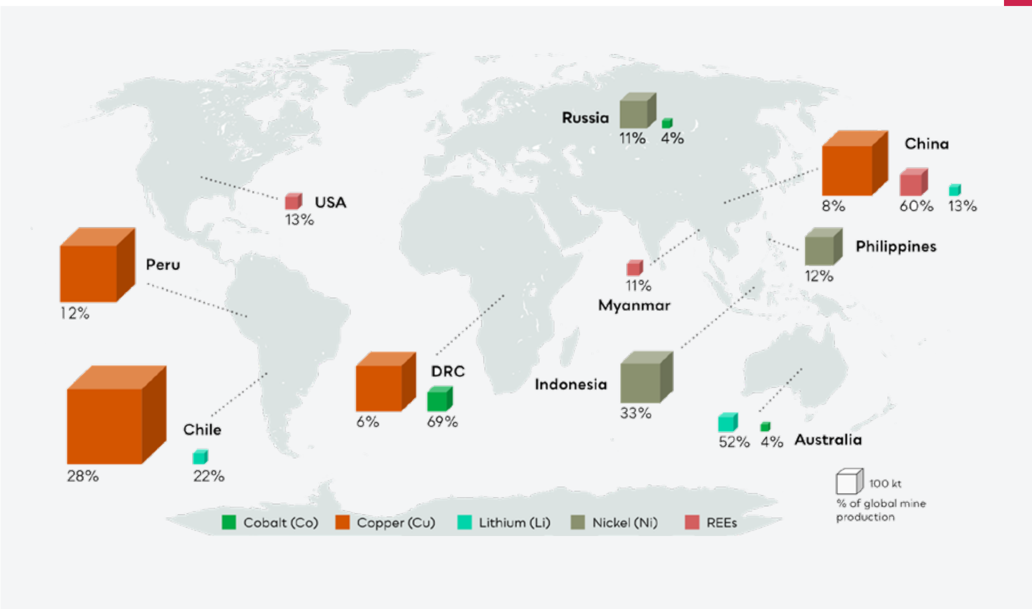


Figure 2: Global mine production in 2019.
Data: USGS[14].

companies in the 1930s feared that copper resources would not be able to satisfy the demand of an already then booming industry[18]. In 1972, in their report *The Limits to Growth*, Meadows et al[19] again shed the light on the topic, proposing a model for the depletion of non-renewable natural resources. Their contribution opened the debate on the feasibility of infinite growth on a planet with known finite physical boundaries.

What exactly are resources?

Geological data is often categorized into *resources* and *reserves*, for which a variety of definitions can be found. Most follow a two-dimensional framework, focusing on the *level of geological knowledge* and the *economic feasibility* of extraction.

The United States Geological Survey (USGS) defines a resource as *"a concentration of naturally occurring [mineral] in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible"*[14]. Differentiation is made between resources that are identified with a certain level of confidence, and those that are still undiscovered. Always following the USGS's definitions, the reserve base is *"that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth"*[14]. Reserves are then the *"part of the reserve base that could be economically extracted or produced at the time of determination"*[14], with different nuances depending on the level economic feasibility (see Figure 5a).

It is then clear that **reserves and resources are not the same as 'all there is' in geological terms exclusively[3]: they are a subjective categorization of mineral commodities which is also based on a variety of economic, technical or social criteria, referred to as *'modifying factors'*.** Consequently, since the techno-economic context of mining is always prone to variations, those definitions do not designate steady amounts of commodities, but dynamic ones, as the USGS and a number of authors highlight[14]: resources can turn into reserves, and vice versa, for several political, economic, cultural or technical reasons[20] (see Figure 5b).

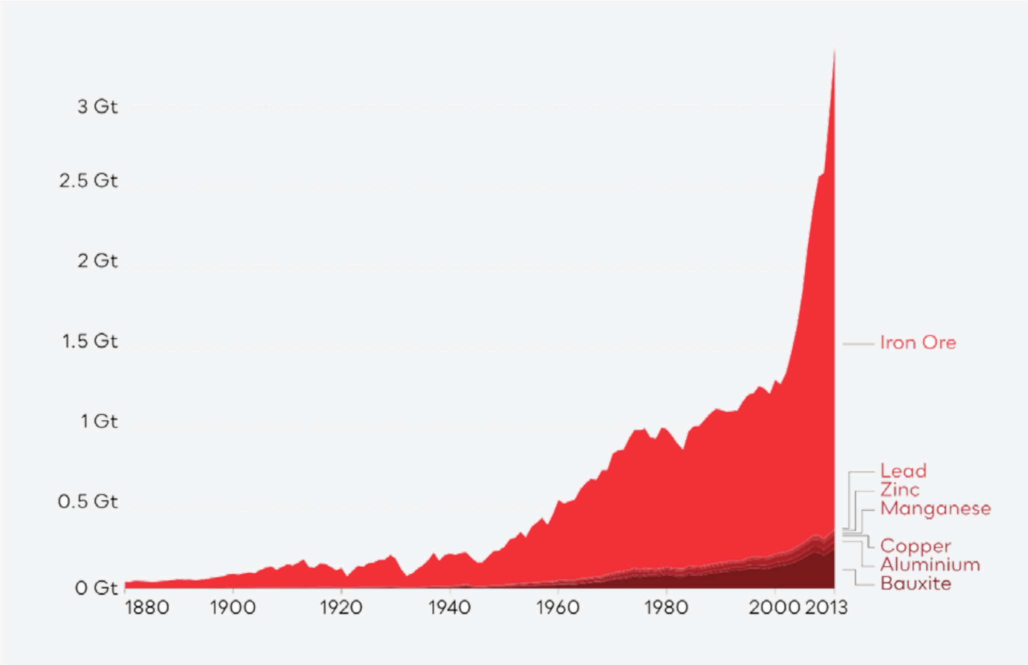


Figure 3: Historic metal production in the world. Adapted from Our World in Data, Clio Infra, USGS.

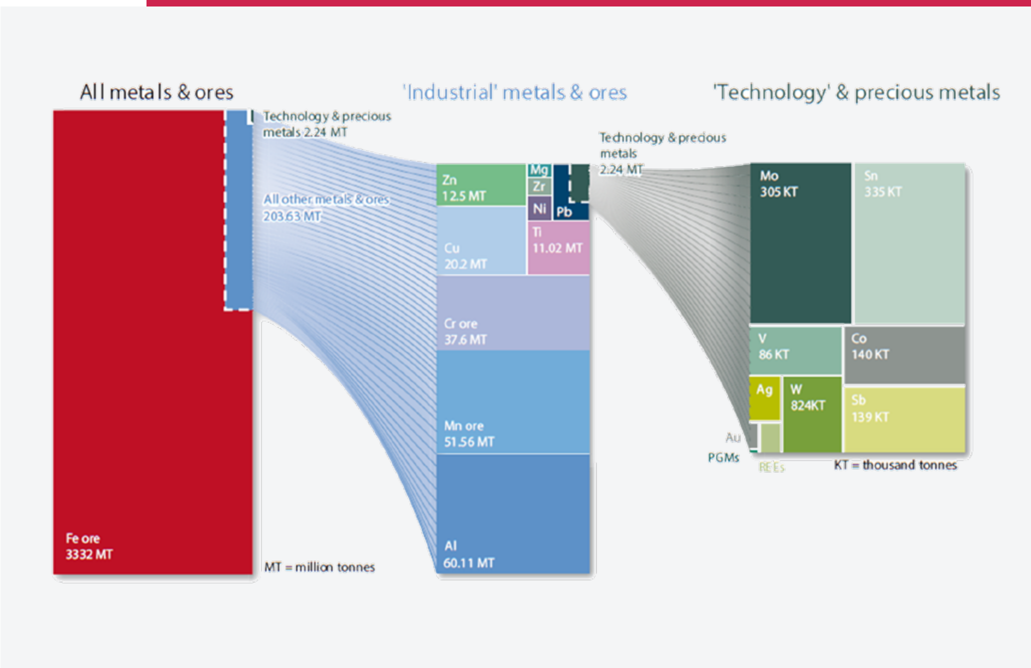


Figure 4: Global production of primary metals and ores in 2017 [16].

BOX 3

How much is mined in the world?

Global metal production is currently higher than ever before in history[6]. Since we have been exploiting metal commodities, global mined quantities have only increased, especially in the wake of the 'Great Acceleration' from the 1950s[15] and with the emergence of China in the 2000s. As can be seen on both figures, individual metals are mined at very different scales. Iron (Fe) represents, in tonnage, around 94% of all mined metals; other base metals (mainly Al, Mn, Cr and Cu), about 6%; technology-critical metals are, comparatively, produced in very small quantities.

It is important to note that **there is, to date, "no institution in the world with the capability of evaluating all the mineral deposits on Earth"[22].** Global reserve estimates follow a probabilistic approach, for there is no way to physically measure the entirety of minerals contained in geologic deposits of the Earth's crust. Current global estimates are mainly based on exploitation data from mining companies[23], which do not follow a scientific but a strategic approach, potentially resulting in a biased picture of reported reserves. Corporate data might be completed with further elements from state authorities (such as the BRGM in France), models, or knowledge from academic articles[18]. This results in a heterogeneous mix of information with various levels of uncertainty. The goal of organizations such as the USGS is to compile and harmonize data in order to provide a general picture of known resources at the global scale. However, it should always be kept in mind that such estimates are indicative, always bound to evolve, and not exhaustive by nature – often resulting in a wide range of values[7].

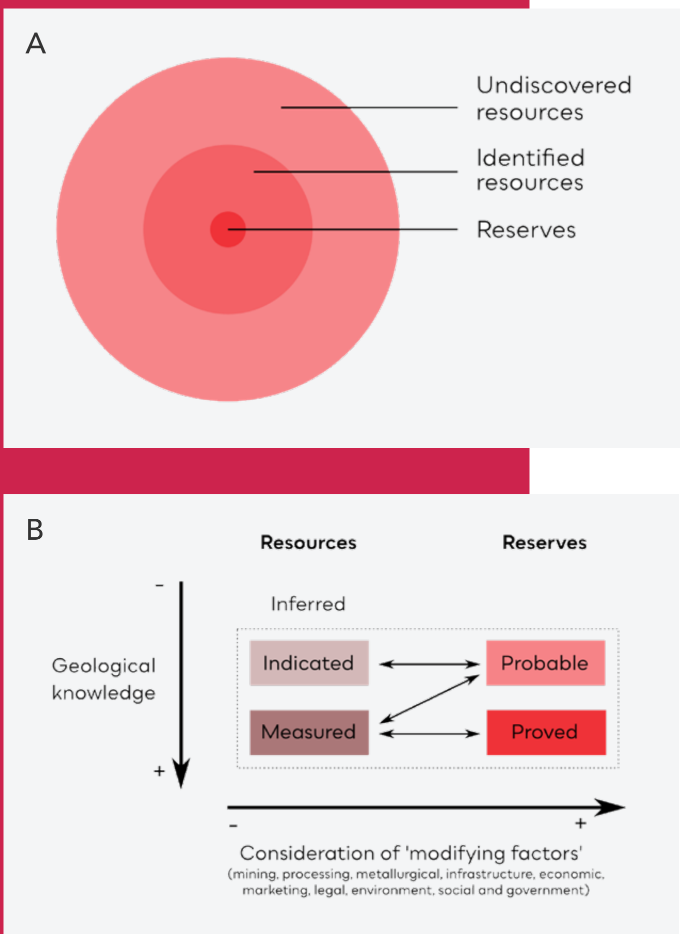


Figure 5: a) Schematic representation of resources and reserves (adapted from Graedel et al.[11]) – **b)** Representation of reserves and resources, as used by the JORC (Joint Ore Reserves Committee), highlighting the dynamics of the classification[21].

Resource depletion

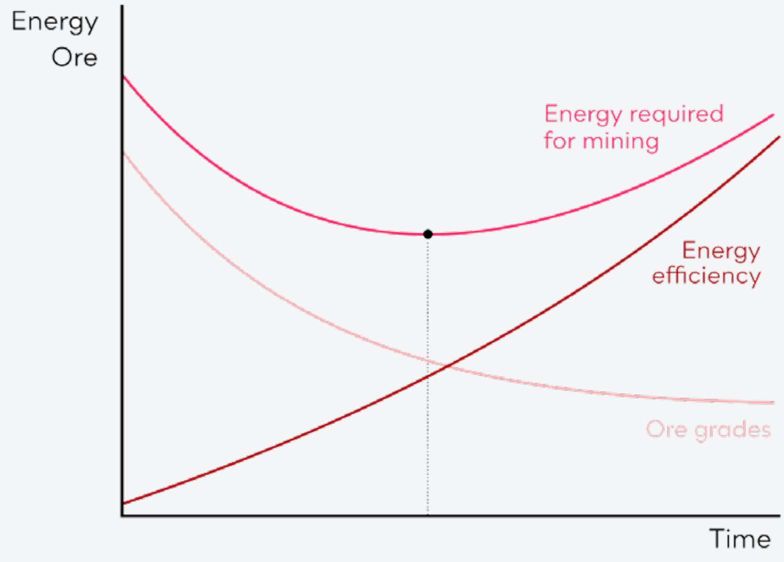
Given the nature of resources and the way they are estimated, observing the depletion of specific commodities at global scale is particularly challenging. A number of indicators provide different insights in that regard: the concentration in mined ores, the evolution of supply or of commodity prices are generally examined in order to predict or assess the potential exhaustion of a particular resource.

Declining ore grades: a matter of energy

Decreasing ore grades have been observed over the last decades for a number of mined elements at global scale[24]. Such a phenomenon might at first seem like a rather obvious sign of increased resource scarcity -since one would a priori think that the most concentrated ores are exploited first. While this is true to some extent, exploited ore grades can also be influenced by a large diversity of factors, which also need to be taken into consideration.

The tendency to exploit ores with lower metal contents can be partly explained by technical

Figure 6: Qualitative representation of the limits of energy efficiency improvements (enabled by technological enhancements) in the mining of commodities with decreasing ore grades, highlighting a tipping point as described by Vidal[25].



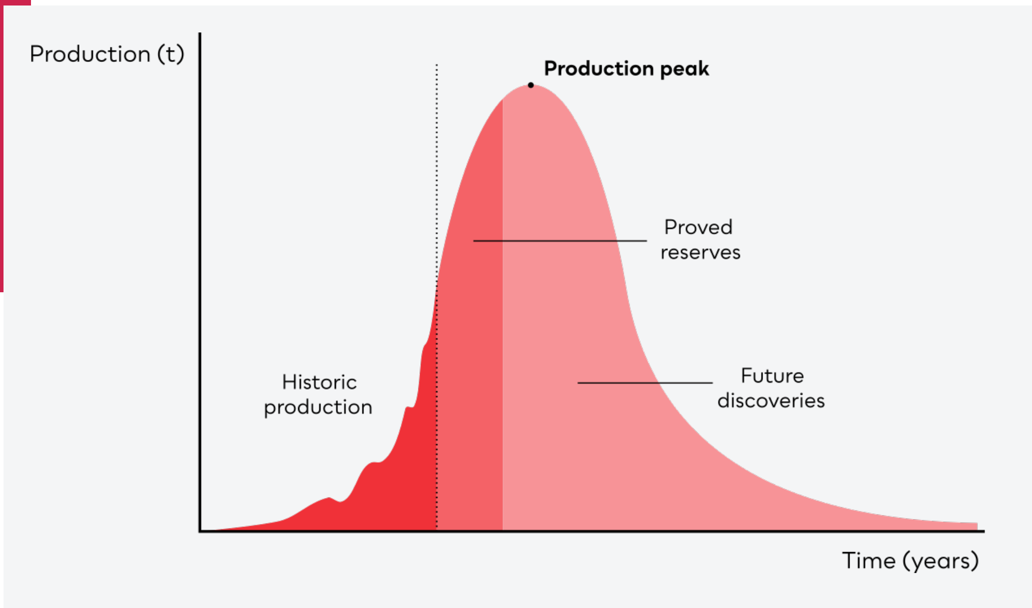
improvements, which enabled higher energy efficiency and productivity[25]. New exploration techniques combined with a better understanding of geological phenomena have enhanced screening processes[8], allowing to find previously undetected, less concentrated deposits. The size of a deposit plays a major role in the economic balance of a mine: because of economies of scale, a larger site with lower concentrations might be more interesting to exploit than a smaller one with higher grades[23]. **Globally decreasing exploited grades are not a clear sign that the richest deposits are getting depleted:** the first deposits to be exploited are often not the richest, but the most accessible[18] – actually, a quantity of rich sites are still left unexploited.

Therefore, the evolution of ore grades should be interpreted with caution: it remains a sensible indicator at the scale of an individual site but is not an absolute sign of global geological depletion. This does not mean that the tendency of the mining sector to exploit lower concentrated ores should raise no concern. Although the energy efficency of mining process increased annually by

Mined ore concentrations that decrease globally can result from a variety of factors, and are not necessarily a sign of incoming resource depletion.

1-2% for aluminium (Al) and copper (Cu) over the 20th century[25], such an evolution is inherently limited by the laws of physics. According to Vidal[25], there is a **tipping point after which the gains in energy efficiency enabled by technological enhancements are not enough to compensate for the increase in energy needs for extracting lower concentrated resource** (as qualitatively represented in Figure 6). This, in a context of rapidly changing energy systems, is a particularly challenging issue, which will be discussed later.

Figure 7: Qualitative representation of the evolution of commodity production according to Hubbert's peak theory.



Peak metals?

The idea of a peak in metal production emerged from the peak oil concept, theorized in the 1950s by Hubbert[26]. Referring to oil resources, Hubbert postulated that the evolution of yearly production in a specific region follows a bell-shaped curve, growing exponentially in early stages, then slowing down around an inflexion point, after which the growing rate decreases to zero until the peak is reached. Production then decreases until the resource is exhausted (see Figure 7). Although such a theory rather succeeded in forecasting the peak in US conventional oil production in the 1970s, since then technical innovation and the discoveries of unconventional oil have nuanced the conclusions[7].

Peak models follow a logistic approach, supposing that the *Ultimate Recoverable Resource (URR)* is known[22]. While this might be true at national scale or for an individual deposit[7], as in Hubbert's assumptions for oil, the nature of resources estimates makes it particularly challenging on a global level: it is "nearly impossible"[27] to accurately assess if a supply peak is being reached, or to predict when it is going to happen[22].

Applied to metals, the concept faces further limitations. Minerals are present in a continuum of concentrations in the Earth's crust, while oil is confined to specific fields, which is very different in terms of geological availability. Another major difference lies in the distinct natures of oil, which cannot be recovered after use in combustion engines, and metals, which are not destroyed and can be reused or recycled[3, 28].

When looking at historic record, one observes that decreases in production have mainly been driven by variations on the demand-side[11, 25], rather than on the supply-side. **Peak models for metals are thus often criticized for being overly simplistic[18]** and deterministic, ignoring the nature of causal effects in minerals markets[28], hence failing to predict the real variations in commodities supply[11].

Static range and the dynamic nature of resources and reserves

Another indicator often used when discussing resource depletion is the *ratio of reserves to production (R/P)*, also called *static range*[23]. For a particular commodity, dividing the amount of global reserves (in tons) by the

Interpreting the R/P ratio is confusing on the long term because of the dynamic nature of resources - this indicator should be used as a short-term indicator solely.

annual extraction (in tons/year) gives a value in years, that would represent the remaining time before the considered resource is exhausted at current extraction rates *(depletion time)*. For example, in 2019, 2.61 million tons of nickel (Ni) were produced in the world, for total reserves estimated by the USGS around 94 million tons[14]: at this rate, nickel reserves would be depleted in 36 years. This becomes even more alarming when considering the increasing needs for annual extraction by the energy transitions, which will drive static ranges down.

However, such an interpretation of the static range of a commodity can be misleading. When looking at historic production data, no evidence of a clear decrease of this ratio can be found for most elements[27] – see, for example, the evolution of the static range of copper (Cu) in Figure 8. Such a phenomenon is once again explained by the dynamic nature of resources, which can become reserves depending on modifying factors. For instance, an increase in demand can boost investment in mining operations and lead to increased exploration, which in turn results in parts of the resources being upgraded to reserves to meet the demand[78].

Some authors thus suggest using the static range only as an "early-warning" indicator, a "snapshot of a dynamic system"[22]: if that value decreases below a decade, it might be impossible to open enough new mining sites in time to catch up with demand, given

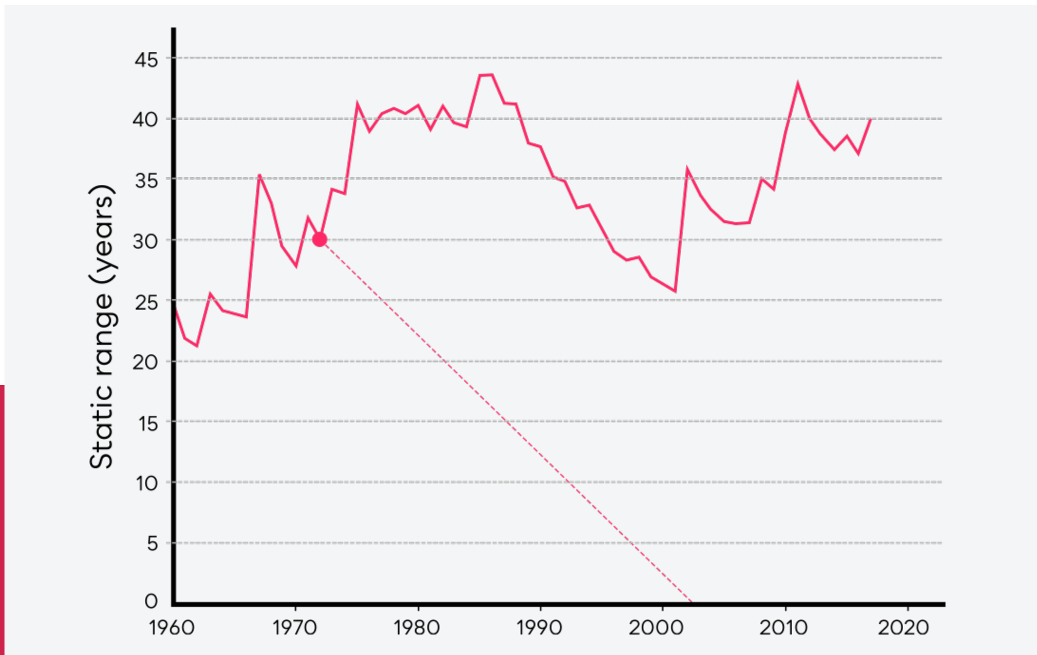


Figure 8: Evolution of the global static range for copper (Cu).
Adapted from Schmidt[23] and USGS.

the slowness of the development process of mines (16 years on average[5]). **The static range is thus more relevant as a short-term indicator than on longer timescales[27].**

Is the fear of depletion justified?

Based on the historic behaviour of the metals market, and considering the definitions of reserves and resources, **geological availability does not seem to be the main issue for most metallic commodities.** For Lee et al[6], "physical scarcity will most likely not be among possible limiting factors". Mudd & Jowitt conclude that within the next decades, "physical resource depletion is not a genuine cause for concern, but rather the growing social, political, environmental, technological and economic risks and impacts from mining are likely to have more and more impact on whether given resources actually make it into production"[29].

The question is certainly a nuanced one. Vidal[25] highlights that conclusions based on historic observations might not necessarily stay true for future evolutions of the metals market, partly because of limitations to technological innovation that might occur at a certain point. Such observations generally focus on a few commodities, which might not depict a general behaviour applicable to the whole diversity of metals of the energy transition. It is also important to note that the lack of comprehensive geological data further limits our understanding of resources, providing only a partial view of the real availability of commodities[22].

The availability of metal commodities is mainly a problem of supply that should be assessed in a comprehensive way, by considering a variety of socioeconomic indicators – using, for instance, the concept of criticality.

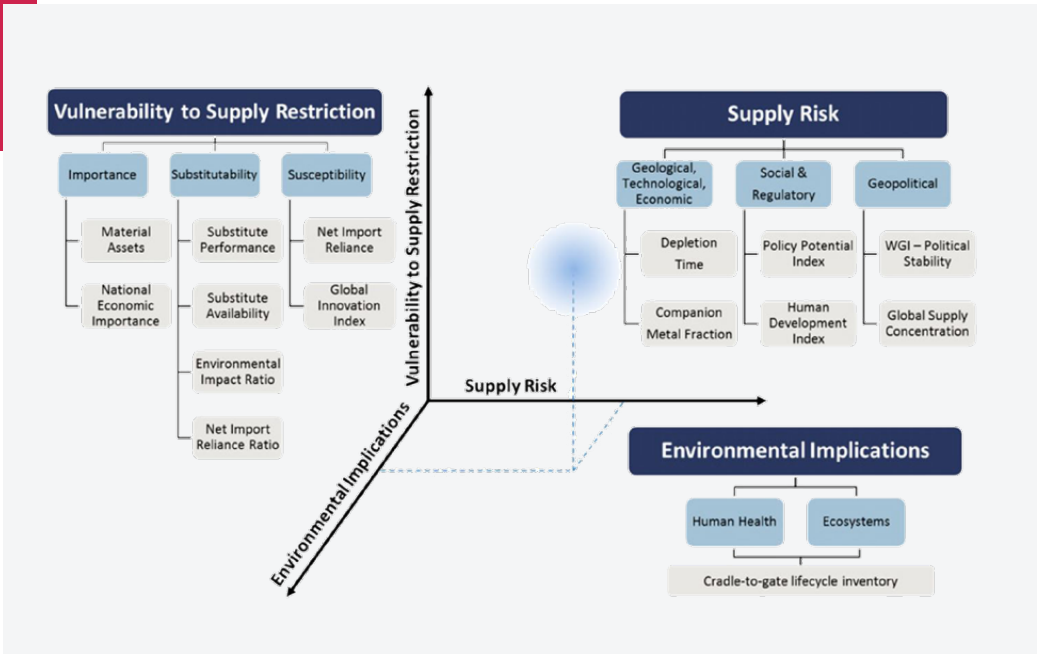
Most studies seem to agree on the fact that **the main challenge with most metallic resources, in the next decades, is not so much an issue of stocks, but one of fluxes,** directly related to the capacity to extract the required amounts. The question should thus not be thought of in terms of geological availability only, but rather by following a comprehensive approach that clearly acknowledges the dynamics of reserves and resources of the individual metals, covering a variety of political, environmental, and economic aspects.

Criticality

Several authors and organisations have focused on developing **comprehensive frameworks to define and quantify the criticality of mined elements.** The United States National Research Council launched in 2006 one of the first initiatives to establish a list of minerals whose supply was deemed critical to the US industry[30]. The assessment, based on two indicators, namely *importance of uses* and *availability*, served as a base to further initiatives, and the concept of criticality framework has been extended to include further dimensions and indicators.

Since 2011, the European Commission regularly updates a list of critical raw materials (CRMs)[31], based on its own methodology[32].

Figure 9: The 'criticality space' for mineral commodities developed by Graedel et al.[33].



Another methodology is the criticality space proposed by Graedel et al., which comprises three dimensions, namely *supply risk, environmental implications and vulnerability to supply restriction*[33]. Each dimension is composed of a number of indicators, detailed in Figure 9, that depend on the considered level of analysis (corporate, national or global) and timescale (medium-term or long-term). The geological component is still present through the 'depletion time' indicator, but now constitutes only a small part of a much broader set of parameters.

This multidimensional approach allows a more nuanced, non-binary analysis[34]: **there is no such thing as 'critical' and 'non-critical' commodities, but a range of materials that are more or less critical in a particular context** or given a certain set of parameters. Such an approach is not without flaws, though. Finer analyses with a diversity of indicators require a larger amount of data, preferably of high quality, which is challenging for a number of metals[33]. The variety of developed frameworks leads to heterogeneous results, often tinged with subjectivity – for instance when it comes to weighting the different indicators[35]. Some authors highlight that criticality is always relative, much depending on the scope of study. They conclude that criticality should be considered merely as an indicative tool to target specific issues, unable to provide a complete picture of resources vulnerabilities: "no single approach is suitable for all time scales or all interested parties"[34].

The future supply of metals

Metals demand for the energy transition

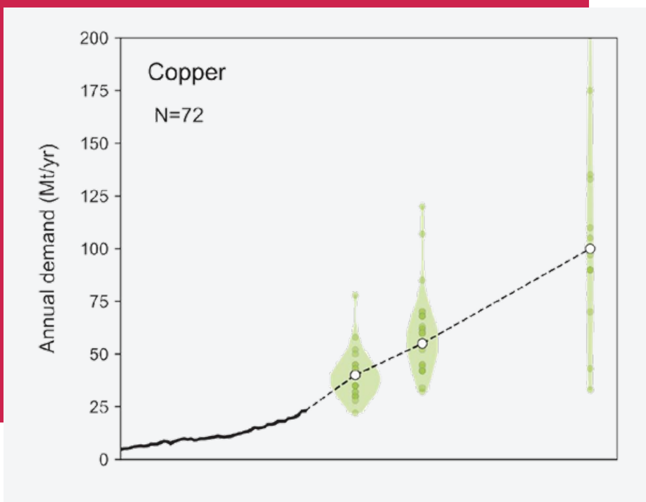
As shown in Box 1, the metal commodities needed for low-carbon energy technologies are very diverse. This makes establishing projections of future demand a particularly complex task, that strongly depends on the actually implemented energy mix, which is itself influenced by a variety of aspects.

BOX 4

Non-energy uses of metals

The present document focuses on the links between the energy transition and metallic resources. Of course, energy uses of metals only represent a part of their total demand. Uses in buildings, industry or infrastructure currently represent about half of copper (Cu) applications[44], while energy uses, around 20%. This share is likely to increase significantly – according to the IEA, around 40% of Cu and as much as 80-95% of lithium (Li) consumption could be attributable to energy uses by 2040[5]. Considering the evolution of non-energy uses therefore adds an additional level of uncertainty in estimating final material demand by 2050.

Figure 10: Range of estimates for annual copper (Cu) demand (time horizons 2030, 2050 and 2100) [45]



Evolutions in prices and learning curves might turn in favour of one or the other technology. Political choices will also play a crucial role. For instance, even if nuclear power is a low-carbon energy technology that requires small amounts of resources per energy unit compared to PV for example[5], it faces significant acceptance challenges in a number of countries[36]. Technological innovation might lead to changes in the shares of the individual technologies and their subvariants – the PV market, currently dominated by crystalline silicon panels, might be more diverse in a few years with the development of thin-film technologies, which have very different material needs[37].

A number of scenarios have been developed to analyse possible pathways for global energy supply and demand by 2050 – some in line with Net Zero objectives, some focusing on 100% RE systems[38–43]. First of all, those scenarios show significant disparities in terms of the projected total final energy demand – ranging from 245 EJ in a 'Low Energy Demand' (LED) scenario[42] to about 700 EJ in more energy-intensive projections[43]. Another major difference lies in the expected contribution of each energy technology to the total demand, with very diverse energy mixes considered. **As for metals demand, this translates in a large variety of estimates, in terms of both total tonnages and shares of individual metals** – although all projections agree on the fact that the demand for both base and technology-specific metals will see significant

Having a variety of estimates for the metal demand, all scenarios highlight a significant increase in demand for the energy sector – with, for some metals, a likely increased share of energy uses in the total demand.

to drastic growth patterns in the coming decades. According to the International Energy Agency (IEA), for example, batteries will be a "major force" of minerals demand, representing nearly half of the estimated growth for clean energy technologies by 2040[5]. Consequently, lithium (Li) demand is expected to rise significantly – the World Bank estimates the annual demands for Li and graphite to increase five-fold by 2050 compared to 2018[37].

Vulnerable supply chains

The strong and diverse increases in material needs for the low-carbon energy transitions may exacerbate vulnerabilities of the metal markets, leading to tensions or even supply disruptions. These could, in return, considerably hamper the transformation of global energy systems, resulting in "more expensive, delayed or less efficient transitions"[5] – and, consequently, in missed climate targets.

Metals supply chains are exposed to a certain number of risks, which can be of varied natures: political, structural, economic, environmental, geological, technical, or societal[46]. The metals market is very unstable, characterized by a very high price volatility, especially for minor metals, which is closely linked to the variations in supply and demand[47]. This section briefly discusses some major vulnerabilities that might represent serious bottlenecks to the energy transition.

Long development times

As the IEA[5] and a number of authors highlight, the **ability of the mining industry to respond to the upcoming booming demand is limited by a structural parameter: its slowness.** Deployment times from deposit discovery to the beginning of production are long, generally comprised between 10 and 15 years for most metals[22]. Considering the capacity of both the existing sites (some of which are reaching the end of their exploitation time) and the mines currently under construction,

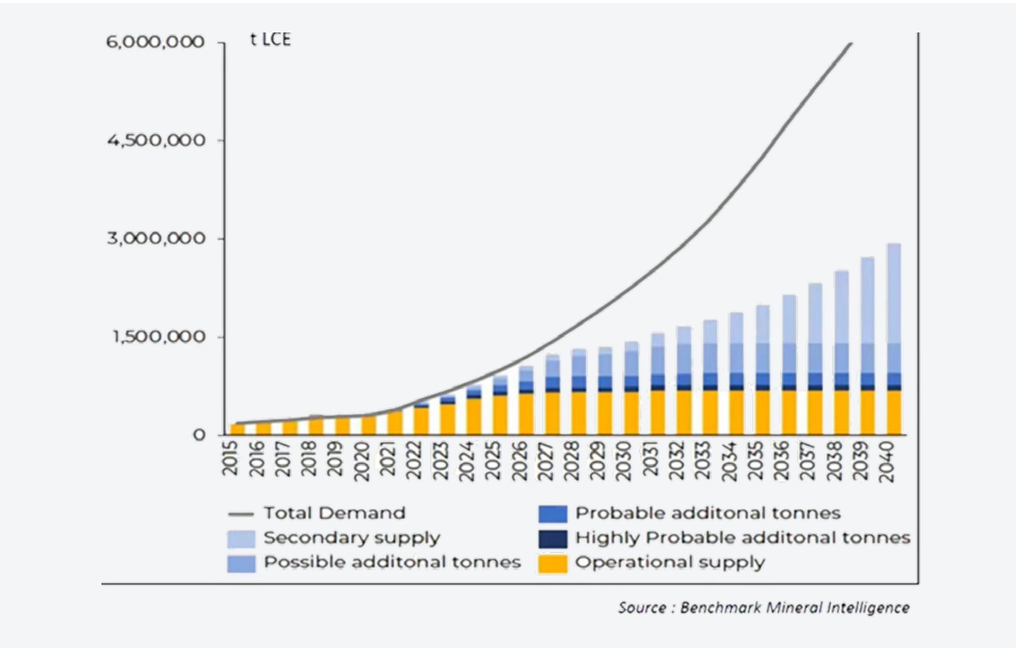


Figure 11: Forecast of lithium (Li) market balance, showing the potential deficit in producing capacities to meet future demand. Source: Benchmark Mineral Intelligence

it is possible that primary demand for lithium (Li), cobalt (Co) and copper (Cu) exceeds committed mine production before 2030[5].

The energy-resource nexus

Resources and energy are sometimes referred to as a 'nexus'[23]: the energy transition relies heavily on the mining and refining of metals, activities which, in turn, require massive quantities of energy – it is estimated that metal extraction and refining consume between 7 and 10% of the global primary energy production[48]. Most of these processes are still mainly based on energy from fossil fuels. The transition to energy mixes with higher shares of RE systems, which are intermittent and have lower energy densities, will be challenging to the mining industry[22], especially if ore grades continue to decline as highlighted previously. This could result in higher energy expenditure, sometimes referred to as the 'energy-scarcity' nexus[49].

BOX 5

Cobalt: a case in point of ESG concerns

The Democratic Republic of Congo (DRC), which has one of the lowest RGIs worldwide, is currently the world's main cobalt (Co) producer, with about 69% of the extraction as of 2019[14]. Congolese cobalt (Co) is mainly a by-product of copper (Cu) – other sources worldwide also include nickel (Ni) deposits for instance. Issues such as poor working conditions, with numerous cases of child labour, are frequently reported. DRC is located in the 'African copper belt', a major productive area for Cu, which is also one of the world's ten most polluted areas[38]. Such considerations raise concerns over the future of cobalt supply[52]. A strategic shift to alternative or less cobalt-intensive battery chemistries is already observed in the energy storage industry, and Co demand and supply might significantly evolve in the upcoming years.

Geopolitics

The heterogeneous distribution of mineral reserves described previously is a potential source of tensions on supply chains. Conflicts of interests between countries have already been observed in the past. For instance, the so-called "rare earths crisis" in 2010 resulted from China's decision to reduce export quotas for REEs, on which the country has a near-monopolistic control – this was especially directed towards geopolitical and economic rivals, such as Japan, which faced unofficial boycott[13]. This led to unprecedented price spikes worldwide and a very tense market. Given the dominant position of China in the refining sector, and the generally intricate geopolitical situation of the market, it is not impossible that such phenomena occur again in the future. Since "none of the current international agencies has a mandate to plan, oversee or realize efficient and effective exploitation of mineral resources"[50], the supply of necessary metals is still very dependent on isolated and potentially conflictual strategies.

ESG concerns

The *Environment, Social and Governance* (ESG) dimensions are used to assess the sustainability of a company's activities. ESG concerns are growing in importance among the actors of the mining industry.

The question of governance notably has emerged as a central topic in a geopolitically tense market, since conflicts and unstable governments can ultimately lead to supply disruptions, which can be dramatic if the considered countries have an important share in worldwide supply[50]. An estimated 44% of global mineral reserves are concentrated in countries with a weak to poor *Resource Governance Index* (RGI)[6] – a composite score developed by the Natural Resource Governance Institute that "assesses the policies and practices which authorities employ to govern their countries' oil, gas and mining sectors"[51].

Climate stress

While metals will be needed for climate change mitigation, the adaptation side should not be neglected. Water stress is a good example. Mining activities can contribute to polluting groundwater, and require significant amounts of water (for drainage, dust suppression…) – demand can go up to about 200 m^3/t_{Cu} for Chilean copper mines, depending on the process type[53, 54]. This can compete with a number of other uses, such as irrigation or the supply of drinking water. Water is already a critical resource in more than 30% of mining regions[55], a phenomenon expected to intensify and spread to a larger number of countries in the upcoming years because of climate change[56].

Towards material-efficient energy transitions

If the geological availability of metallic resources is not an absolute structural limitation to their utilisation, this does not mean that boundless and uncontrolled extraction is desirable either. Firstly, because of the number of negative externalities related to mining operations, such as pollution, impacts on health and difficult working conditions. But also, because of the vulnerabilities and limitations described previously. For those reasons, a number of strategies are contemplated as solutions to reduce levels of primary extraction, such **as light-weighting, substitution, fabrication yield improvements, more intensive uses, lifetime extension, reuse and remanufacturing, and recycling[45].** In this section, we will focus on the strategies that, in the case of metallic resources, receive the most attention: substitution, recycling and increased material efficency.

Supply at scale might be hampered by, notably: the slowness of building the required mining capacities, increased complexity of extraction, a very intricate geopolitical context, and the negative impacts of mining activities.

Substitution

Most commonly, substitution designates the act of replacing a particular material by an alternative one with equivalent properties, which under specific criteria offers a better overall compromise. The use of alternative materials can be a relevant strategy to lessen the demand for the most critical commodities. Substitution has, for instance,

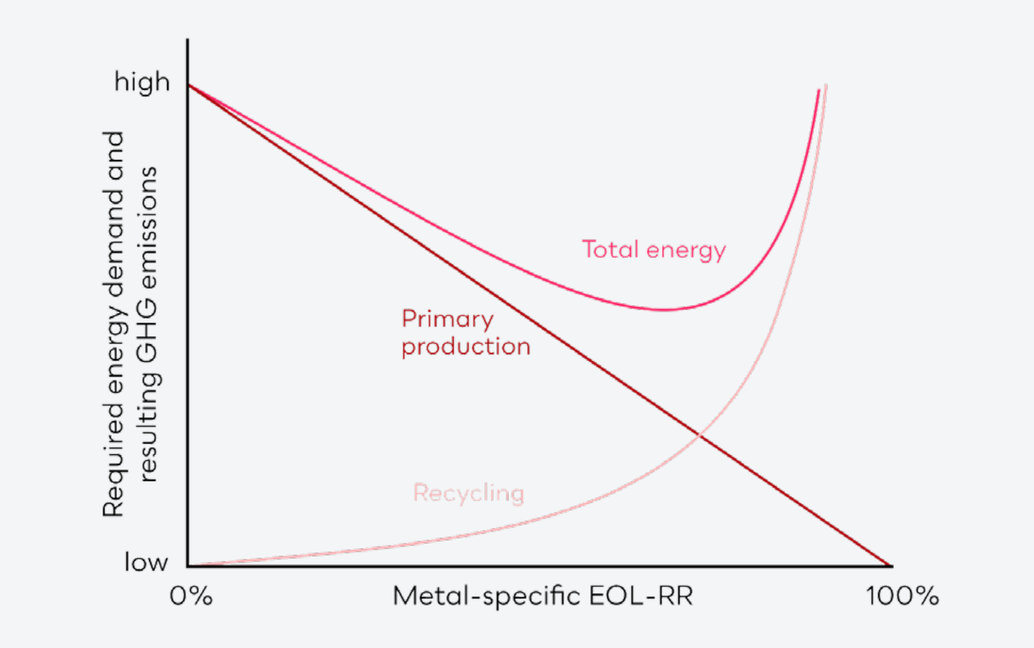


Figure 12: Theoretical representation of total energy expenditure depending on the level of recycling of a particular commodity, showing the optimum recycling rate – here, total metal production is limited to the scope of recycling activities[59].

already been observed in electricity networks, where copper (Cu) has to some extent been replaced by aluminium (Al), lighter and less expensive[5].

Obviously, some metals are easier to substitute than others. Studies have tried to define a substitution potential for each

Reducing dependency on primary metals extraction can both lessen supply vulnerabilities and reduce some negative impacts of the mining industry. The potential impacts of behavioural changes and sufficiency strategies should also be considered in that regard.

individual metal, which is not an easy task given the variety of metals and uses[4]. A few of them have no known suitable alternative, such as rhodium (Rh), used in catalytic converters, or neodymium (Nd), necessary to permanent magnets[11]. Given the large amounts of base metals and the wide range of their applications, they are also among the most difficult to replace[46]. A further difficulty lies in the fact that constituents in modern technologies are most often chosen as they provide the most exquisite performance[4].

Because of this, substitution often comes with a less satisfying performance: replacing silver (Ag) with copper (Cu) in crystalline silicon cells reduces the conversion efficiency of solar panels[2]. Compromises are not always negative though, and substitution can sometimes be in line with other imperatives: finding alternatives to silver (Ag), which currently constitutes 0.1% of the weight of a PV panel but 20% of its monetary value, is already discussed as a relevant way to drive technology costs down[6].

Recycling

The recycling of raw materials, or secondary extraction from the "urban mine"[57], has long been present in the public debate on resources management.

Although metals are in physical terms almost infinitely recyclable, a certain number of limitations appear in technical applications. Losses can occur at every step of the lifecycle of a technology[58]. Dissipation designates the use of minerals in very low concentrations (*spice metals*) observed in a number of modern

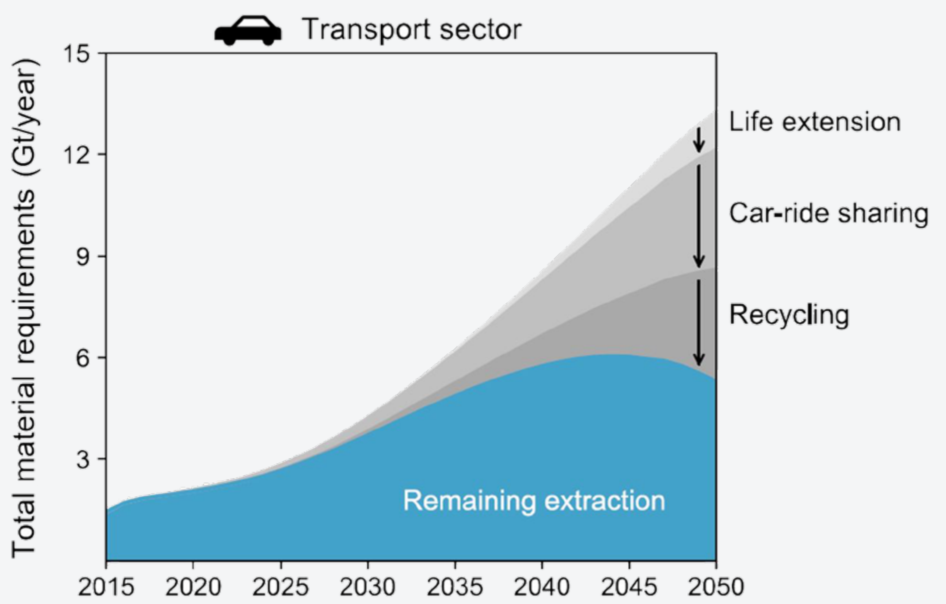


Figure 4: Estimated reduction potential of total material requirements associated with metal production for the transportation sector [45].

BOX 6

Reducing material demand

Although gains in energy density have improved the material footprint of batteries, projected needs for lithium (Li) and other battery components still remain significant. Current and planned extraction capacities could soon be overwhelmed by demand. The potential for secondary supply is limited until the first generations of used batteries reach their end-of-life phase – most-often contemplated strategies are the recycling of the individual metals and the direct reuse of old batteries for applications that require lower-performing equipment, such as stationary storage for electricity grids[5]. Other technical solutions such as light-weighting are still left under-explored in most scenarios, despite showing interesting potential[62] – be it through the use of lighter materials or reduced vehicle sizes. Materials demand of the transport sector could also be reduced by other means: longer ownership of vehicles, car-sharing or shifting to active mobility are examples of changes in consumption habits that could be further encouraged.

Recycling, substitution and material efficiency are examples of strategies that could reduce our dependency on primary extraction of minerals. However, strategies to reduce demand, such as material substitution or gains in material efficiency, come with a number of significant limitations.

technologies: a smartphone microchip contains about 70 different metals[11]. This makes collecting particularly challenging[23]. Recycling processes are also complexified by the wide use of alloys, which require additional effort to separate the individual metals[58].

Such complex industrial processes come with increased energy needs, which might be conflictual with the imperatives of the energy transition. Defining an optimum recycling rate is particularly challenging. A rate of 100% would be optimal in terms of resource use but is physically impossible following the second law of thermodynamics – increasing recycling rates require increased energy expenditure[58]. **Very often, the energetically optimum recycling rate, above which energy expense and emissions are higher than those of primary extraction, lies way below 100%[59]** (see Figure 12). This optimum varies significantly with the considered metal, uses and region. For instance, end-of-life recycling rate (EOL-RR) for copper (Cu) in Germany could, at about 50%, already be optimal in terms of energy and GHG emissions[23].

Further concerns over the ability of recycling to meet the upcoming increase in material demand are more structural. Low-carbon energy technologies rely on a number of metals that have historically been exploited only in small quantities, thus presenting an inherently limited potential for reuse in periods of strong demand growth[25]. Building a global energy system takes time, and the lifespans of renewable energy systems generally range between 15 and 30 years depending on the considered technology – a time during which **metals would be 'locked-in', unavailable for recycling purposes[2].**

Material efficiency

The goal of increased material efficiency of individual technologies is to reduce the overall material demand, while providing the same levels of services. Some gains have already been observed, for instance for crystalline silicon PV panels, which nowadays use considerably less silver (Ag) per power unit – needed amounts reduced by a factor of 3 between 2009 and 2017[60]. Similarly, batteries have shown significant increases in density over the last years – a trend that drives the material intensity up, and that is supposed to continue further.

Reducing dependency on metals

The strategies described above are not mutually exclusive: they act as a nexus of solutions that can overlap or compete with each other. Watari et al.[45] insist on the importance of focusing on the whole lifecycle of goods and services. Nowadays most attention is paid to end-of-life strategies such as recycling. However, as seen previously, there is no such thing as a "panacea"[8]: each individual strategy has its own limitations, which is why all the solutions considered here have an important role to play – focusing on one or the other solely might result in suboptimal gains in material efficiency. For those reasons, approaches combining lifecycle analysis (LCA) and material flow analysis (MFA) on a dynamic basis are particularly relevant pathways to establish clear science-based targets[45].

While a lot of material efficiency strategies rely on technical transformations, **socio-economic changes in consumption patterns should not be overlooked[61].** Critical thinking on the end-uses can contribute, through sufficiency strategies, to shape lifestyles that are less dependent on resources to satisfy human needs. It is obvious that irreducible needs for primary extraction will always remain; defining the "acceptable" levels[61] is particularly challenging.

Further readings

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DISCUSSION & CONCLUSION

Will metallic resources be sufficient for the energy transition? Analysing the dynamics of reserves and resources and the historic patterns of metals demand and supply shows that geological availability should not be the main concern for most metals.

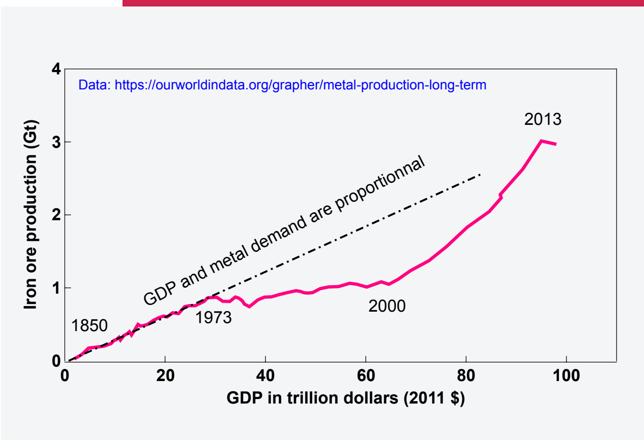
This, however, should not be interpreted as a go-ahead to exploit mineral commodities without limits. Resources and energy form a complex nexus, and the extent of the upcoming demand on an already very constrained market might have major repercussions on metals supply chains in the short- to mid-term. Tensions or disruptions may occur due to a combination of various factors, such as geopolitical conflicts or insufficient investment in mining capacities. Assessing the criticality of metal commodities on an individual basis might provide useful insights to better understand the different supply chains and avoid shortages.

To limit possible bottlenecks, **reducing the dependency of human activities to primary material extraction is a crucial challenge, having the co-benefit of reducing negative externalities of the mining industry.** Commonly contemplated strategies such as recycling or substitution have a great potential, but they are no silver bullet: still under-developed, each of them presents a non-negligible number of theoretical and practical limitations. Thus, it is crucial to implement a mix of pathways that covers the complete lifecycle of technologies and embraces technical as well as socioeconomic solutions. Exploring the interrelations between material use and the economy can help to understand the past, current and future dynamics of resource extraction – and, consequently, in our case, to determine, not so much *whether* metallic resources will be sufficient for the energy transition and during the coming decades, but *how* they will.

This is all the more important since **decoupling economic growth, which up to now has enabled the development of human societies, from material use, is still not achieved at scale[63].** The relationship between Gross Domestic Product (GDP) and metal production, is particularly interesting in that regard. Historically, global metals demand has increased together with GDP, proportionally, until the 1970s. Between 1970 and roughly 2000 (Figure 14a), iron ore production has remained roughly flat while GDP increased, as by-then developed countries reached a saturation level in infrastructure/capita. Production picked up again after 2000 mainly driven by the emergence of China, which now accounts for more than half of the global steel production. Considering non-ferrous metals only (Figure 14b), no trace of such a decoupling can be found anymore and there is an almost perfect proportionality between metal production and GDP up to 2013.

Given the increasingly important role of metals in the upcoming transition, in the light of the analyses provided in the present review, the **relationship between economy and metal demand, and its potential evolution in the future, seems to be a particularly crucial concern, which will be discussed in more details in further investigations.**

The main challenge with most metallic resources, in the next decades, is not so much an issue of stocks, but one of fluxes.



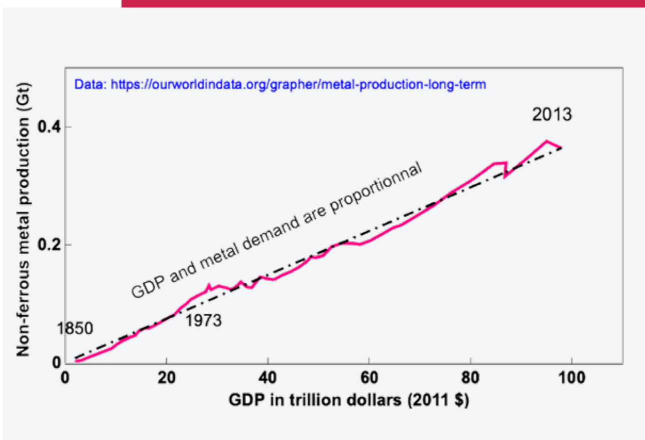


Figure 14: Relationship between metals production and gross domestic product (1850-2013).

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