



Resource accessibility and depletion assessments: bridging the gap between geospheric and anthropospheric mineral resources

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Received: 31 January 2025 / Accepted: 23 December 2025
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Abstract

Continuous population growth and the acceleration in energy transition are raising concerns about the accessibility of mineral resources for current and future generations. Traditional methodologies, such as the Abiotic Depletion Potential (ADP) in Life Cycle Assessment (LCA), try to assess it quantitatively but often overlook the dynamic nature of resources. This paper explores mineral resource depletion, addressing misconceptions and uncertainties while proposing pathways forward. The understanding that the concept of resource is intrinsically related to a function is a key starting point for the discussion. The paper navigates the discourse surrounding resources from both physical and economic perspectives, and underscores the dynamic nature of resources, shaped by technological advancements, societal needs, and economic factors. Beyond instrumental and economic values, the paper proposes to look at accessibility as the main value of resources, bringing the focus to resource preservation along their life cycle. Resource accessibility is governed by three aspects (knowledge, ESG permissibility and technical feasibility), underscoring the ability of a system to conserve the recoverability of resources. Instead of questioning how much is left to be exploited, what we do with what we exploit is the core question for sustainable resource management. Essentially, a fairer production system must be conceived by caring for durability (i.e., enhanced lifetime of products) and material functionality (i.e., societal benefits) instead of flows and profit. Any framework for sustainable resource management should be developed under the lens of critical scrutiny of existing economic and production structures.

Keywords Mineral resources · Resource depletion · Resource accessibility · Resource management · Circular economy · Life cycle assessment (LCA)

Introduction

Organizations have been integrating life cycle thinking, techniques, and tools into decision-making to enable the view of the environmental impacts associated with all stages of a product's life. With the world trend to encourage a circular economy (CE), the mining role has been questioned by the widespread idea that increasing resource efficiency is a requirement for sustainable development (Lèbre et al. 2017). Otherwise, it has also been proved that it would

be unreasonable to think that primary extraction could be entirely replaced by recycling end-of-life (EoL) products in the near or distant future (Allwood 2014). Therefore, instead of extinguishing mining, efforts must be directed to bring sustainability and CE concepts into the mining sector. Since extracting virgin raw materials seems to be inevitable in the near or distant future and mineral resources are not renewable at a sufficient pace to meet our demand, concern about resource depletion arises. Resource depletion refers to the reduction of natural resources and hence the limitations in their availability to current and future generations (Hauschild et al. 2013).

According to Abdallah (2017), “environmental impacts are changes in the natural or built environment, resulting directly from an activity, that can have adverse effects on the air, land, water, fish, and wildlife or the inhabitants of the ecosystem”. One may question if resource depletion is more a matter of supply and demand rather than an environmental

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impact. Effectively, mining activities may have many associated environmental impacts, like deforestation, acidification, air pollution, etc., but there is no “extinction” of mineral species. Moreover, long before extracting the last tons, costs and prices would rise sufficiently to preclude exploitation and eliminate demand. However, one must consider that environmental impact is an anthropocentric concept, focused on the well-being of mankind, which is deeply affected by the accessibility of resources.

The definition of mineral resources accessibility comprises two aspects: availability (the physical presence) and approachability, which integrates technological, economic, societal, and environmental factors necessary for its utilization (Mueller et al. 2017). Therefore, while availability focuses on the existence and estimability of a resource, accessibility addresses the capacity to exploit it, considering a wider array of influencing factors (Mueller et al. 2017). “In brief, availability concerns the physical presence of a resource, and accessibility concerns the ability to make use of a resource” (Schulze et al. 2020).

Natural Resources are one of Life Cycle Assessment’s (LCA) three Areas of Protection (AoPs), between the Natural Environment and Human Health (Dewulf et al. 2015). The availability of mineral resources is a pillar of the well-being of humankind, the primary AoP (Schaubroeck and Rugani 2017). Within the AoP of “natural resources,” the safeguard subject for mineral resources is defined as the potential to make use of the value that mineral resources can hold for humans in the technosphere. Damage, in this context, is quantified as the reduction or loss of this potential caused by human activity (Berger et al. 2020). Nevertheless, there is no explicit reference to mineral resources in the United Nations (UN) Sustainable Development Goals (SDGs), despite the consensus that minerals are embedded within every one of the 17 goals and 169 targets (Franks et al. 2022). The extractive industry is often perceived as having a disproportionate impact on biodiversity and GHG emissions (Oberle et al. 2019), while the metals that empower the new technologies and solutions have no other source than minerals.

Many authors have attempted to develop methodologies to assess quantitatively the depletion of mineral resources, often considering a ratio between extraction rate and natural stock. Guinée and Heijungs (1995) conceived the most accepted methodology within LCA, the Abiotic Depletion Potential (ADP), which was reviewed by Van Oers et al. (2002). It is a mass-based, dimensionless, characterization factor derived by dividing the annual production of a given raw material by the squared assumed stock of a resource. Then, this result is multiplied by the life cycle inventory result (extraction) to produce a potential impact score. This method has been used for more than 20 years in LCA and its core concepts and assumptions are still in debate (Beylot et al. 2024).

Most of the problems around depletion assessments lie around the definition and quantification of the “natural stocks”. Many assessments are based on assumptions that are not geologically supported, often using generalizations for a batch of elements. For example, it is not reasonable to consider the same crustal depth to calculate natural stocks for gold and aluminum, since the deeper the more expensive mining becomes, and the market value of gold allows to exploit it in much greater depth than aluminum does. In addition, it ignores that these two elements occur in hugely different types of mineralization, being current aluminum deposits (bauxites) a consequence of surface alteration while gold concentrations can occur at various depths. Consequently, the current characterization factors for aluminum are underestimated, as they rely on an overestimated ‘natural stock.’ In contrast, the characterization factors for gold may also be underestimated, but to a smaller extent. A proper understanding of what a resource is, and its indicators, is essential for correct resource depletion assessments.

The Committee for Mineral Reserves International Reporting Standards CRIRSCO (2019) establishes the concepts of mineral resource and mineral reserve. Both are classified with the increasing level of geological knowledge confidence of a mineral deposit, as seen in Fig. 1. Considering the technical, economic, political, and social aspects of opening a mine, a mineral resource can turn into a reserve. In other words, the process of converting a mineral resource into a reserve requires a positive evaluation of many modifying factors that would attest to the viability of the deposit to be mined.

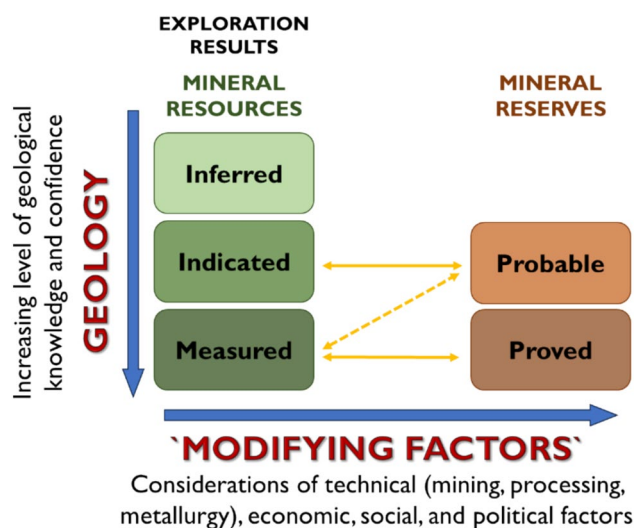


Fig. 1 General relationship between exploration results, mineral resources, and mineral reserves. Source: CRIRSCO (2019). The yellow arrows indicate possible transitions in the classification of a deposit, while the dashed arrow represents a transition that is less likely to occur

Therefore, a mineral resource, according to CRIRSCO (2019), “is a concentration or occurrence of solid material of economic interest in or on the Earth’s crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction”. On the other hand, the committee defines that mineral reserve “is the economically mineable part of a measured and/or indicated mineral resource”. Thus, any reporting based on resources or reserves is a snapshot of raw-material availability at a given point in time given prevailing market (technology, politics, social, etc.) conditions. It does not represent the total stock available to humankind for all time and is not necessarily affected by mining. Consequently, it does not represent all physical stocks, but currently viable stocks in terms of extraction and processing.

The United Nations Framework Classification for Resources (UNFC) (UNECE 2020) brings the view of resources and reserves to a 3D representation by splitting the “modifying factors” axis into “technical feasibility” and “environmental-social-economic viability” axes. Despite increasing complexity, it allows the evaluation of the viability of mining projects and its correct management. Efforts have been invested to apply this framework to anthropogenic resources, given that recycling has gained relevance. However, authors recognize that there is still a lack of robust theoretical concept and framework for mass-balance consistent geological stock estimates hindering resource governance and strategy development (Simoni et al. 2024).

“In nature, nothing is created, nothing is lost, everything is transformed”. The quote attributed to Antoine Lavoisier, a French chemist of the eighteenth century, may raise the idea that resources can be reintroduced into the cycle indefinitely. However, a fraction of the extracted resources becomes inaccessible (i.e., lost) at every stage of the production cycle (permanently or not). Therefore, elements cannot simply disappear unless they undergo nuclear fission or decay, but the use we make of materials is what determines whether they stay in the cycle or dissipate. Beylot et al. (2020) describe dissipative flows as “flows to sinks or stocks that are not accessible to future users due to different constraints that prevent humans from making use of the function(s) that the resources could have in the anthroposphere”. Anthroposphere refers to the part of the Earth system that is created, modified, or maintained by humans for their activities, including all human-made materials, infrastructures, products, and associated processes occurring within society (Baccini and Brunner 2012).

It is not extraction, but dissipation, that makes resources inaccessible. By mining and processing, we are transferring materials from the geosphere to the anthroposphere. Resources are not “lost” when extracted from nature into the anthroposphere, as long as they can remain recoverable

and functional to be reintroduced in the cycle in some way (Berger et al. 2020). As long as resources are accessible in the anthroposphere, there is no depletion problem (Van Oers and Guinée 2016). Therefore, there is a trend to recognize that it is dissipation instead of primary resource depletion that affects the resource availability for future generations (Berger et al. 2020; Mankaa et al. 2024; Owsianiak et al. 2022; Sonderegger et al. 2020). The challenges we face lie more above the ground than beneath it.

This paper will address the problems around abiotic resource depletion assessments, clarifying the main misunderstandings around mineral resources and evocating a parallel between the geosphere and the anthroposphere while proposing pathways forward.

Natural stock misunderstandings

When referring to a resource, the focus is its functionality and not only the element or mineral. That means that materials considered important commodities may become worthless with technological development or regulation policies. For example, there is a tendency to ban toxic elements like mercury and cadmium for environmental reasons even though they can still own a function. Therefore, these elements would lose their role in the anthroposphere and no longer be considered a resource. During the Stone Age, the discovery of obsidian’s sharpness was revolutionary and became an important resource, but when bronze was invented, all obsidian became useless. These examples show that resources can never be considered a fixed parameter. They are created by humans and may vary with technology, policy, creativity, supply, and demand (Wellmer and Scholz 2017).

Grefe et al. (2023) develop the concept of functionality as the capacity of a resource to provide services that contribute to human well-being. Rather than focusing solely on the physical availability of materials, the authors emphasize that resources differ in their functional quality, which can be degraded (loss of performance), downcycled (reduced to fewer services), or fully dissipated (loss of accessibility). Conversely, functionality can be restored through processes such as upcycling. That shifts attention from resource extraction to the deficit of services caused by the loss of functionality. This framework links human interventions to changes in functionality. In doing so, the authors reframe resource depletion as a problem of service provision and human well-being, rather than simple stock reduction.

Tilton (1996, 2003) contend that the debate around resource depletion can include two mental models. One, in a pessimistic view of the future, is based on the fixed stock paradigm (i.e., there is a finite amount of a given resource).

The second is based on the opportunity cost paradigm which views resource depletion more optimistically, as a problem driven by market demand. Drielsma et al. (2016) show that LCA practitioners have vacillated over the last decades between the fixed stock and opportunity costs approaches to access resource depletion potential. These two models offer vastly different views of natural resources. In the fixed stock view, it is assumed that use leads to some form of penalty or reduction in availability. In the opportunity cost view, natural resources are treated more like flows that need to be managed to best meet human demands. Van Oers et al. (2020) define resource depletion as “the decrease of availability of the total reserve of potential functions of resources”, which implies the definition of resource availability, referring to the readiness of a resource for human use.

Resource and reserve

Given the CRIRSCO definition, resources and reserves are not only reduced by extraction but can be diminished or even increased with the modifying factors. This shows that approaching mineral depletion with a “fuel-tank” model is incorrect, which does not mean that mineral resources are unlimited. There is a finite amount of material on Earth, but, from the known fraction of the crust, the recoverable part is not fixed, and determining its extension in a long-term perspective is a tough mission with plenty of speculation about the modifying factors. Resources may increase with the development of exploration campaigns and the discovery of new deposits (and there is still a lot to explore! (Arndt et al. 2017)) or with reserves becoming uneconomic. Reserves may increase by turning resources viable according to the modifying factors (i.e., technology, economy, etc.).

With the development of many electrical solutions in industry, copper has received special attention in the past recent years. The threat of increasing copper consumption due to its good electrical conductivity has raised concern about its depletion. Despite the increasing mine production, the copper reserves have increased significantly over the last years, and from 2010 to 2017 the Reserves/Mine Production (R/P) ratio has been kept at around 40 (International Copper Association 2023). On the last report of USGS (U.S. Geological Survey 2024), copper mine production is estimated at 22 Mt, and global copper reserves are estimated at 1 Gt, which means that the R/P ratio is at around 45.

The significant increase in copper reserves may be justified by the reduced cut-off grade of copper ores globally. A reduction of 25% from 2003 to 2013 was identified and many mining operations had their cut-off grades reduced

from around 1.50% to around 0.50% (Calvo et al. 2016). The increasing demand enables more investments and fosters the development of new technologies and solutions, which may allow the processing of poorer ores. Therefore, it would be wrong to see the decreasing cut-off grade as an indication of depletion, as elaborated by Wellmer et al. (2023). We do not know what global copper resources and reserves will be in 100 years, but we can affirm that current estimates are misleading when assuming they reflect fixed stocks (Tilton and Lagos 2007).

Calvo et al. (2017) compared reported resources for 1995 with those for 2015 for 22 mineral commodities. For 11 of these commodities, the reported resources remained the same, indicating that the increases in resources were enough to compensate for the resources exploited during these years. Ten of the studied commodities had an increase in the reported resources, being tripled in some cases (i.e., cobalt, beryllium, fluor spar, and lithium). Only copper had a reduction in the reported resources, dropping about 10%.

Finally, it is important to notice that the CRIRSCO approach is made to protect investors, and the intended readership for reserves estimates is the community that trades on metal and stock exchanges. These figures are more governed by economic/business constraints rather than scientific considerations, defining, annually, the company’s exploration strategies, since it incurs cost. Note that exploration strategies and costs are not independent of scientific/geological considerations. It is indeed a requirement that they be well-founded in geological science, but they are ruled by other subjective aspects (economics, politics, etc.) that affect their estimation and reporting.

Even though eight of the top ten produced commodities are industrial (non-metallic) minerals, these are often poorly documented when assessing resources and reserves. Investments in mineral exploration are much higher for metals although they represent less than 3% of global mineral production while industrial minerals account for more than 80% (Franks 2020). Of course, metals create a greater economic value than their production volume would suggest, but the revenue produced with industrial minerals is underappreciated. For example, the value of metals production in the United States in 2021 was US\$33.8 billion compared to US\$56.6 billion for industrial minerals and construction materials (Franks et al. 2022). The lack of detail in the reporting of reserves in this sector prevents depletion assessments. In this case, the parameter that could govern the maximum amount of depletion is the permit issued to the mine. Therefore, it would be the government that defines, perhaps unwittingly, the resource depletion.

Ultimate Reserves (UR) – The fixed stock

Drielsma et al. (2016) recommended that “fixed stock parameters such as crustal content are the only measures for estimating mineral depletion that fit within the logical construct of life cycle assessment as it is currently standardized by ISO 14040 series of standards”. However, much of the crustal content is indeed assumed unavailable. Availability criteria should be addressed with estimates based on technically, geologically, and socio-economically coherent assumptions when thinking about depletion in the very long run. The definition of these criteria is often under discussion given the complexity of the problem and the difficulties that dealing with such variable factors in a long-term pose. It presents a kind of subjectiveness since it may rely on a certain prediction of the behavior of these variants.

As an attempt to find the best metric for the mineral stock, Guinée and Heijungs (1995) proposed using “ultimate reserves” (UR). The authors estimated it by multiplying the average natural concentration of the resources in the earth’s crust by the mass of the crust. It is important to notice that this concept conflicts with the official CRIRSCO (2019) definition of reserve and conceives UR including non-conventional and low-grade materials and ordinary rocks, encompassing the whole continental crust. Even though elemental abundance ratios are well known (Rudnick and Gao 2014), referring to UR to quantify available stocks provides their upper limits, since much of this material may prove unsuitable for mining and/or processing (UNEP 2011).

Accounting for the whole crustal content would indeed encompass a large amount of resources that are inaccessible for human use because of technological constraints. At a certain point of dilution, it becomes unfeasible to recover elements/resources. Any depletion based on chemical abundance alone (e.g., Crustal Scarcity Potential (CSP) (Arvidsson et al. 2020)) will be fundamentally flawed unless an estimate of the proportions of different mineral species is made (and these proportions are very different for every element since it involves the capacity to form concentrations) (McNulty and Jowitt 2021). Therefore, it is possible to consider that technology evolves and keep in mind that resources and reserves may vary with many factors (Arndt et al. 2017), but facing the problem with such open and hypothetical scenarios would lead to a hopeful view that counts on the technological development of a future civilization.

Mineralogical barrier and log-normal distribution

Which fraction of the whole crust content could be considered extractable and recoverable? Elements may be present in diverse forms in the crust. Silicates, oxides, sulfides, carbonates... an element may be present in a variety of minerals, but often just some of them are technically recoverable and economically viable. The distribution of the elements in the Earth’s crust can be approximated by a log-normal curve (Andersson 2021), i.e. the elements are more likely to be present in lower grades in the crust and anomalies (ores), the functional material, are a minor part. However, the log-normal approximation may mislead when hiding that it is the combination of the distribution of the different forms in which a given element may occur. The so-called mineralogical barrier separates these functional minerals, i.e. the mineral host, from the technically inaccessible fraction of minerals in which elements are in a more tightly bound form (Skinner 1979).

The mineralogical barrier may be clear for some elements like chromium, which is obtained only from chromite. Despite chrome (Cr) being present in generic rocks, these are not used as a source of the metal (due to the high entropy and consequent amount of energy required to recover it), with chromite (FeCr_2O_4) being the preferred source. This may not be that clear for other elements like magnesium (Mg), a special case in which many sources can be used to obtain magnesia (MgO) or Mg metal. MgO is the second most abundant oxide in the mantle (37.80%) (McDonough and Rudnick 1998) and represents 4.66% of the crust (Rudnick and Gao 2014). Between carbonates, silicates, hydroxides, etc., Mg can also be recovered from salts, seawater, and brines. Of course, among these, the cheapest sources requiring less energy will be preferred, but there is no clear mineralogical barrier.

Ultimate Recoverable Resources (URR)

Although crustal content is considered by some authors the only base with the desired stability for assessing resource depletion, it is not meaningful even in the long term if the entire crust is considered. Schneider et al. (2015) addressed this problem by trying to define a meaningful and stable metric for mineral stocks, considering the accessibility of resources rather than only their geologic abundance. Based on existing practices and some assumptions, the authors proposed a way to calculate the Ultimate Recoverable Resources (URR).

Schneider et al. (2015) refer to Ultimately Extractable Reserves (UER) and other authors use Extractable Global Reserves (EGR) (Drielsma et al. 2016; UNEP 2011). In this paper, URR is the equivalent term to represent the estimate of the ultimate fraction of a resource in the Earth's crust that can realistically be extracted and processed. Schneider et al. (2015) simply follows the assumptions of UNEP (2011) which is to assume that 0.01% of the total amount in the crust to 3 km depth will ultimately be available for carrier metals (i.e., host element or main product) and 0.001% for accompanying elements (i.e., by-product).

However, the authors estimated URR for a batch of elements with the same criteria. This is not geologically appropriate because various elements may have distinct origins that result in different types of mineralization, varying the size, shape, and depth of the deposits. Additionally, it is not economically viable to assume that all elements can be extracted and processed at the same cost, as their values differ. It is unreasonable to expect companies to dig as deep for lower-value minerals like limestone compared to high-value metals like gold. Similarly, it is unrealistic to expect to find bauxite at the same depth as copper, since the first is formed by superficial alteration of aluminosilicates while the second is often associated with hydrothermal activity deep into the crust.

It is important to note that, unlike UR, URR is not a fixed parameter. Its determination stands on the foreseeable future and the respective speculated economic and technological conditions. Therefore, it depends on the interpretation that each author would have and on the coherence of their assumptions. URR is a moving target and can be highly affected by the development of new technology (e.g., reducing URR by making alternative commodities more competitive; increasing URR by new discoveries aided by new exploration techniques and campaigns). It is important to stress that not fixed does not mean unlimited.

Technological change is occurring at an increasingly rapid pace, which significantly limits the reliability of long-term forecasting (Nagy et al. 2013). Additionally, rising energy costs with depth and environmental pressures will progressively gain significance in terms of mineral production costs and consequently impact mineral availability in the coming times (Humphreys 2013). Given that, it is far from clear that it would be possible to make reliable estimates of URR now or in the foreseeable future (Tilton 2018). URR is a “known unknown” (West 2020). Despite the complexity of predicting future technological conditions, there are still some methodologies that aim to assess an estimate of “undiscovered resources”, given a constant technological condition. Singer (2010) shows that improved density models can make probabilistic estimates of undiscovered resources with reduced uncertainty.

In summary, UR (Guinée and Heijungs 1995) misleads while considering a fixed stock and encompassing materials that are not accessible and not suitable for processing (and will probably never be). Therefore, it can represent the upper limits but cannot be considered a stock even in the very long run. In the search for a more meaningful metric for the stocks, Guinée and Heijungs (1995) contend that URR would be the best choice but poses tough difficulties to be determined. It is a moving target that requires a high level of geological knowledge of each resource and its specificities and relies on speculative assumptions of hard-to-predict variables such as economic and technological development in the long-term perspective. “For better or worse, the future is inherently uncertain” (Tilton and Lagos 2007).

Given these difficulties, some authors prefer to assess the future availability of mineral commodities based on measures that reflect what society must sacrifice to obtain it (i.e., the opportunity costs), instead of physical measures. To do so, tracking real commodities' prices is one option, as developed by Ardente et al. (2023). Watson and Eggert (2021) investigated the relationship between metal prices and physical indicators and found that crustal abundance explains 21% of the observed variation in prices, while energy requirements in production had the biggest influence (43%). It shows that metal prices are only partially influenced by the element abundance and its variation depends not only on their availability, but also on many other hard-to-predict variables and complex dynamics (economics, politics, etc.). Therefore, it is impossible to forecast accurately the future trajectory of commodities' prices because of the significant uncertainties around the speed and the path of innovation and technological advancements.

While price is more associated with supply, demand, and other market dynamics, the value of a resource includes a notion of “value to society”, i.e., the capacity to serve societal needs, its functional value. The value of a resource is intimately associated with its accessibility and functionality to society and these are to be preserved for responsible resource management.

Resource value - from geosphere to anthroposphere

If the uncertainties around the quantification of the URR prevent us from measuring it accurately, rough estimates available in the literature (Rostek et al. 2023; Wellmer et al. 2023; West 2020) suggest that the true size of URR is sufficiently large and, therefore, is not a driver through CE. This does not mean that we should not care about how we manage the resources in and after use, but that resource scarcity is not the concern driving it. There are more

immediate reasons (e.g., climate crisis) as to why resource conservation in and after use is a good idea.

With the increasing stimulus to build an industry that is more aligned with CE principles, anthropogenic resources should be part of the picture when assessing resource depletion. Fostered by climate change, recycling has been a key action to reduce CO₂ emissions in the refractory industry. By using recycled refractory aggregates, we can reduce the use of primary raw materials (which require a CO₂-intensive sintering process) and add value to spent linings. This illustrates the importance of considering the anthroposphere in the equation and how urban mining (Xavier et al. 2023) is key. Figure 2 shows a parallel between the geosphere and the anthroposphere in the case of refractories.

Recycling supplies part of the demand for a resource but will never be enough to supply it completely (i.e., create an infinite loop) due to inevitable losses associated with every stage of a production process. This would only be possible

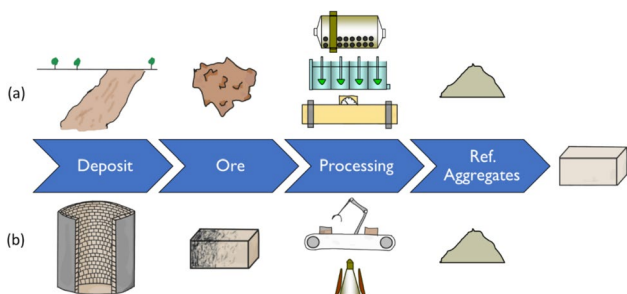


Fig. 2 Upstream of refractory manufacturing: primary and secondary production. **a** Primary raw material production - mineral deposit, ore, processing (mineral processing - grinding, flotation, calcination), primary refractory aggregate. **b** Secondary raw material production (urban mine) - “Deposit” (spent lining), “ore” (spent brick), processing (sorting, crushing), secondary refractory aggregate

in a decreasing demand scenario where the losses could be compensated. Moreover, a technological transition scenario may constrain recycling, since many resources may not yet be available in the urban mine and would therefore need to be supplied from primary sources.

Furthermore, recycling can be a smart strategy since it departs from an already refined material, avoiding energy-intensive processes and the extraction of primary raw materials. However, recycling may also rely on important energy needs and is also subjected to some sort of mineralogical barrier, e.g., the use of alloys can increase the entropy to levels that hinder the recovery of the original resources. Figure 3 represents both primary and secondary production routes in terms of embodied energies. Note that in the case of anthropogenic resources, unlike in the geogenic case, the deposit is not given, which requires an effort of collection in terms of energy and governance.

Dewulf et al. (2021) point to opportunities to do better by reducing compromising actions rather than measuring circularity. The authors identified six human actions that compromise accessibility (or availability) to secondary raw materials: emitting, landfilling, tailing, downcycling/dispersing into the anthroposphere, hoarding, and abandoning. The assembly of many elements in high-tech applications hinders the accessibility of these elements. Complex alloys, plastics, paints, ceramics, etc. have elements that any known economically viable technology cannot recover. This is called ‘lost by design’ by Ciacci et al. (2015). As one of the strategies to better manage resources, industries should consider recycling at the conception of their products. If we can engineer something, we should be capable of dismantling and recycling it. Of course, ‘lost by design’ is unavoidable for some products but minimizing it should be a focus.

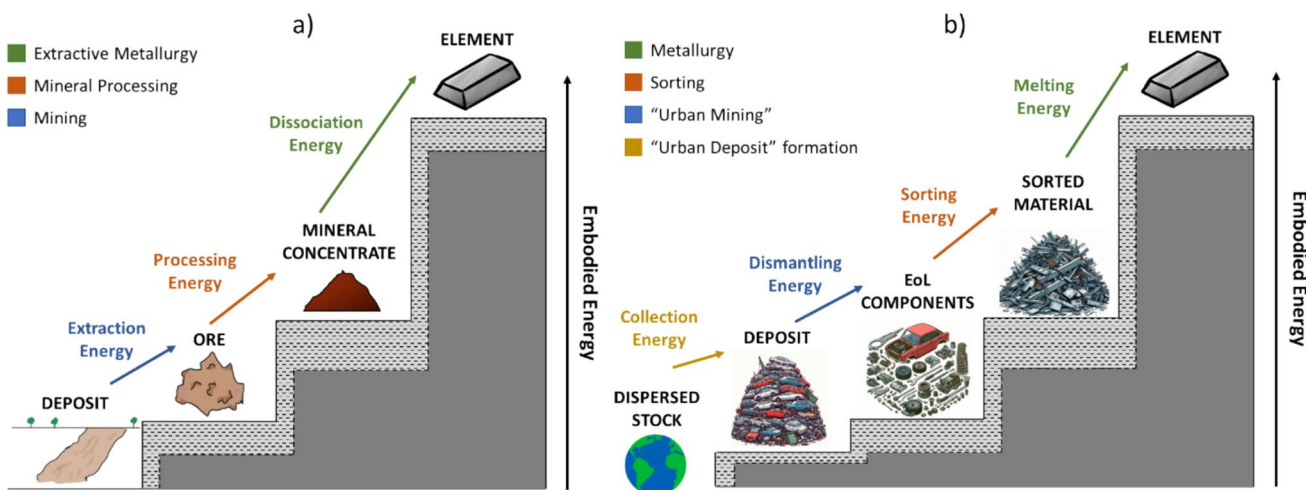


Fig. 3 The valorization of a) geogenic and b) anthropogenic resources. Note that in b), collection energy is required since the deposit is not given as in the primary route. Dashed lines are to show that energy may vary from one resource to another. Not to scale

Applications that keep their functions for a long time also prevent materials from serving as a secondary raw material source. The occupation-in-use (OIU), better elaborated by Beylot et al. (2021), is also compromising the availability of secondary raw materials. In 100 years about half of all extracted metals are expected to remain in use, most of which is iron. Specialty metals will likely be fully lost, while only 4% of ferrous and 16% of precious and non-ferrous metals are expected to be in use by that time (Charpentier-Poncelet et al. 2022b). However, this does not mean that products should last less (i.e., premature obsolescence). It is indeed desirable that the elements save their functions in the anthroposphere for as long as possible. Occupation-in-use is highlighted here, to remind that a fraction of the anthropogenic stocks is in use and, therefore, not available to other users of the resource.

One may argue that time can be the key parameter to evaluate the accessibility of resources, i.e. estimate the accessibility based on the time required to access its instrumental value - the utility or experiential benefit derived from a product or service when it fulfills human needs and desires through its functions (Charpentier-Poncelet et al. 2022a). Recently, Dewulf et al. (2024) developed the Contribution to Inaccessibility (CTI) as a resource management methodology to measure how human activities compromise the accessibility to the instrumental value of resources. The authors estimated the Time to Accessibility (TTA), i.e. the time to access the instrumental value of a resource, to derive accessibility factors. This allows us to evaluate how a process, product, or use impacts the accessibility of a resource. However, note that the estimate of TTA, like price-based estimates, is highly context-dependent since we will be able to recover materials rapidly or not given the presented burdens and constraints (technology, economy, etc.). Finally, it appears that technological constraints are a common root of these parameters. Therefore, from a technical point of view, energy seems to govern the accessibility of resources, alongside ESG and the degree of knowledge (of the volume estimate).

Within the LCA field, damage to mineral resources is defined as the reduction or loss of the potential to make use of the value that mineral resources can hold (Berger et al. 2020). While studies refer to instrumental/functional value of resources, the referred value lies on the finished product and on its function, on their utility to humans (Charpentier-Poncelet et al. 2022a). This logic misses an important aspect to evaluate the loss of value as a resource itself, once it focuses on the final function. For example, a high-tech instrument using a lot of different elements tightly bound in alloys may excel its functions and add impressive economic and instrumental values to the resources used. However,

manufacturing such an instrument implies damage to the value of such elements as resources (i.e., damage to the accessibility of those metals), once dismantling and re-processing becomes a tough task given the increased entropy. The value of a resource relies on its knowledge (of volume, quality and location), ESG permissibility and on its recoverability. In summary, preserving the value of a resource relies on the ability of a system or process to preserve the accessibility (or recoverability) of its resources. Therefore, the higher the dissipation rate and entropy, the more significantly the system's potential to preserve the resources is compromised.

Inspired by UNFC (UNECE 2020), Fig. 4 represents the classification of resources based on the concepts discussed in the previous section. This representation is not on scale and evaluates the technical feasibility, the environmental, social, and governance (ESG) permissibility, and the degree of knowledge of a deposit. It is important to notice that, by covering UR and URR, this representation goes beyond UNFC, which covers resources and reserves. Moreover, while the UNFC includes the economic aspect on the E-axis, our representation considers ESG factors, with the economic aspect covered indirectly under the technical feasibility axis. We will be technically able to recover a resource given the technological constraints, which are closely related to economic aspects.

Each of the three axes of this representation has a barrier that limits the use/accessibility of resources. First, the technological constraints make the resource technically unfeasible to recover. Second, there is a limit stated by ESG factors, i.e., policies that restrict accessibility to resources due to social or environmental aspects (e.g. the global agreement to forbid exploration of the Antarctic continent). The third limit is related to the knowledge of the deposit, which is, in the case of geogenic resources, the maximum depth that can be achieved by current exploration techniques. A similar idea can be applied to anthropogenic stocks. Hence, the resources are governed independently by these three dimensions, and the greater the permissibility, recoverability, and intelligibility, the higher the resource accessibility.

In general, mining and refining raw materials invest energy to obtain the elements/resources from an intricate matrix in which they are embedded (ores). The resources and their properties are then accessible (known, permissible, and recovered) for any desired function. Note that resource accessibility carries additional nuances and differs from economic or instrumental value. Of course, copper is more expensive when used in an electronic circuit than in a high-purity ingot, because the first implies further processing (i.e., further costs that imply increased price) and has gained a function (i.e., increased instrumental value (Dewulf et al. 2024)). On the other side, after producing an electronic circuit, copper is

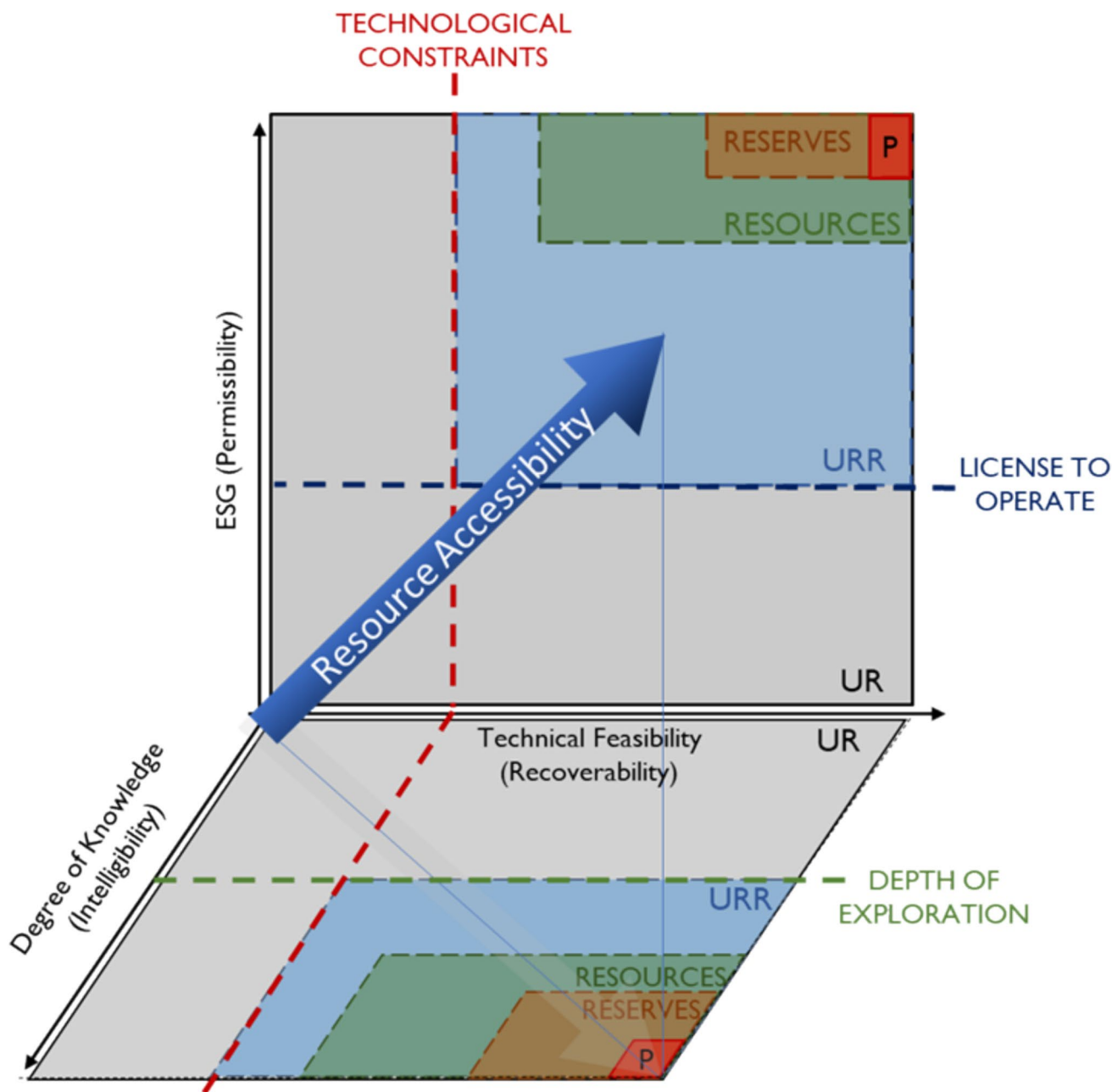


Fig. 4 Classification of resources. P=Mining production; URR=Ultimate Recoverable Reserves; UR=Ultimate Reserves

diluted in a complex matrix and will require resource and energy investments to be recycled. Figure 5 presents how resource accessibility can vary in the case of copper.

While inserting materials into the anthroposphere, resources gain economic and instrumental value since they own a function, but they have its accessibility compromised: they are embedded in more or less complex matrices (products), the “ores” of the urban mine. Differently from the primary sources, these “urban ores” are created by humans who can decide their composition and design to

possibly facilitate the reprocessing of these materials and consequently their accessibility. However, in a system that privileges large flows and profits, the design of a product tends to serve cost reduction and production speed priority over durability and societal benefits. For that reason, while functionality remains below economics in the priority list, resources will be serving the capital before society. The conception of a sustainable and fair socioeconomic metabolism must not escape the critical scrutiny of our economic and production systems (Parrique 2019).

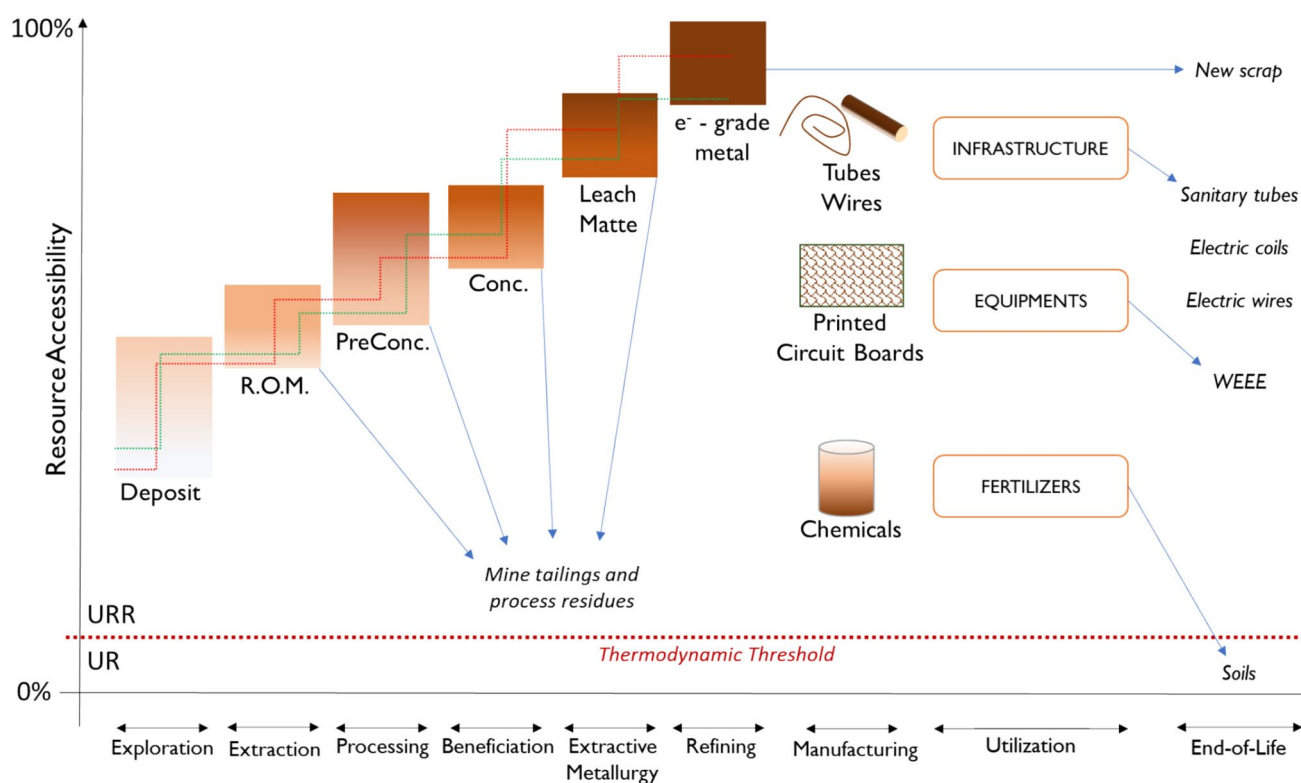


Fig. 5 Variation of resource accessibility through hypothetical copper life cycles. Green and red lines are to show that the value may vary according to the processing path

Conclusions and outlook

This paper has traversed through intricate concepts around mineral resources, reserves, and their depletion, shedding light on misconceptions, uncertainties, and potential pathways forward. As we conclude this discourse, several key insights emerge, guiding us toward a more holistic understanding and action-oriented perspective.

First and foremost, the discourse on resource depletion necessitates a departure from simplistic, static models toward a nuanced appreciation of dynamic systems. The dichotomy between fixed stock paradigms and opportunity cost frameworks underscores the multifaceted nature of resource availability. Recognizing the interplay of geological, economic, technological, and societal factors, we confront the inherent uncertainties that pervade our estimations of reserves and URR. Despite these uncertainties, studies have shown that URR is sufficiently large, and the cause of eventual supply threats do not come from resource scarcity in most cases. In depletion assessments, the delineation of UR serves as a simplification effort, with many unsupported and speculative conjectures. Despite these obstacles, the imperative of dealing with the future trajectory of mineral resources remains unchanged.

With a contribution to the framework for the classification of primary and secondary resources, we reveal opportunities for improved resource management, showing how their accessibility is governed by three independent dimensions and their limits: (1) technical feasibility (technological constraints), (2) ESG permissibility (license to operate) and (3) knowledge (depth of exploration). Within this framework, the parallel between the geosphere and the anthroposphere emerges as a transformative potential in our quest for sustainable resource management. Estimates based on secondary dimensions like price or time are attempting to assess accessibility indirectly, with the influence of other complex and highly context-dependent factors.

The idea of attributing depletion potentials to resources, based on their extraction rate and natural stock is inappropriate. The extraction of primary raw materials represents not more than a transfer from the geosphere to the anthroposphere and a consequent valorization of the material (i.e., giving it a function). Resources are not “lost” when mined, but when they are not well managed in the anthroposphere. Therefore, tackling the compromising actions to the accessibility of secondary raw materials is key to sustainable resource management. Above all, a production system that rewards durability (i.e., enhanced lifetime of products) and material functionality (i.e., societal benefits) instead

of flows and profit is the path towards a fairer relationship with resources. This means, adopting resource management practices that respect the environment and demonstrate solidarity with future generations.

Acknowledgments This paper is part of a PhD project within the CESAREF consortium. This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement no.101072625.

Author contributions João Victor MENEZES CUNHA: Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing. Eric PIRARD: Conceptualization, Methodology, Writing – Review & Editing, Supervision. Thomas DRNEK: Supervision.

Data availability No data was used for the research described in the article.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies During the preparation of this work, the authors used Copilot Designer to generate some of the icons presented in Fig. 3. After using this tool, the authors take full responsibility for the content of the published article.

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