

Methodological and Ideological Options

Squaring the circle of the circular economy. The need to properly account for scarcity to guide mineral resource management

Cati Torres^{a,*}, Alicia Valero^b, Antonio Valero^b, José Manuel Naredo^c^a Ecological Economics, Applied Economics Department, University of the Balearic Islands, Cra. Valldemossa, km. 7.5, 07122 Palma, Illes Balears, Spain^b Energy Engineering, Research Institute for Energy and Resource Efficiency of Aragón (ENERGAIA), University of Zaragoza, Campus Río Ebro, Ed. CIRCE, c/ Mariano Esquillor Gómez 15, 50018 Zaragoza, Spain^c Department of Urban Design and Spatial Planning at the Higher Technical School of Architecture, Polytechnical University of Madrid, Av. de Juan de Herrera, 4, Moncloa - Aravaca, 28040 Madrid, Spain

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ABSTRACT

Over the last decades, extractivism and its derived socio-ecological impacts have increased exponentially, suggesting that prices of minerals are poor indicators of their absolute scarcity. Aware that we need to move towards a more circular economy (CE), we propose a methodology which builds on the use of an exergy-based indicator of absolute scarcity to create the much-needed taxonomy of mineral substances to make CE-oriented policies more effective. This indicator will not only allow overcoming the limitations usually attributed to physical indicators as scarcity's proxy measures. Transcending the usual mass-based approach to absolute scarcity, it warns that depletion is more about the loss of mineral quality than quantity, which is fundamental in a physical world governed by the Law of Entropy where ore grades decline over time. Even more, beyond enabling the calibration of economic tools to ensure we move towards circularity, this indicator can also set the basis for designing depletion charges targeted at raising social awareness and putting upward pressure on prices well before reserves are exhausted. Our methodology will also allow providing new insights into mineral price formation. By warning that we must learn from the biosphere, we argue that society can reach sustainability if it increases the use of renewable resources while moving towards that of abundant, recyclable, and physically easy-to-obtain mineral substances. In so doing, not only we show the importance of interdisciplinary work. We also point to the relevance of integrating weak and strong sustainability approaches in economics, thus avoiding the existing divorce between monetary and physical analyses.

1. Introduction

In a context of massive and exponentially growing resource use and waste generation globally, the debate on the scarcity of mineral resources and the environmental impacts of mining has intensified, as shown by the 2015 interdisciplinary Workshop "Mineral Resources in Life Cycle Impact Assessment: Mapping the Path forward" held in London (Schmidt, 2019). Current institutional concerns about sustainability focus on the need to move towards a circular economy (CE) (Achillas and Bochtis, 2020; Morales et al., 2021). Strategic policy packages containing CE regulatory instruments have rapidly emerged at all governance levels (European Commission (EC), 2015, 2018, 2020; Khajuria et al., 2022; Sorin and Einarsson, 2020; United Nations

Environment Programme (UNEP), 2013). Seeking to mimic the biosphere's model, policies pursue to transform the linear industrial process into a circular one by closing the material cycles through the reuse of waste. However, designing CE-oriented strategies based on the current prices for minerals, which are non-renewable resources (NRR) at the basis of the economic process, is expected to be ineffective. The fact that we are quickly approaching the depletion of mineral reserves¹ (Valero et al., 2014) suggests that prices are too low thus stimulating global extraction over recovery and recycling (Naredo, 1996, 2001). It suggests that prices are poor indicators of the absolute scarcity of mineral resources thus leading to their inefficient allocation through markets.

The fact that the prices of NRRs do not reflect their absolute scarcity has long been of concern to economists (Hall and Hall, 1984; Tilton,

* Corresponding author.

E-mail addresses: cati.torres@uib.cat (C. Torres), aliciavd@unizar.es (A. Valero), valero@unizar.es (A. Valero).¹ While mineral resources are the resources as contained in ore deposits that can be extracted under certain economic and/or technological conditions determining varying economic and/or technological barriers, mineral reserves are resources existing in known deposits (Ortiz, 1993).

2002). It has been thirty years since Solow (1992) stated that assuming that their ordinary prices accurately reflect scarcity feeds a “semi-fiction” as, in practice, prices “reflect all sorts of distortions arising from monopoly, taxation, poor information, and other market imperfections”. The long-standing geopolitical moves to control their prices are one of these imperfections, as well exemplified in the case of oil (Fernández-Durán and González-Reyes, 2018; Martínez-Alier and Roca, 2015) where prices reflect OPEC’s decisions rather than scarcity (Hanley et al., 2007). Extractive activities also generate important external costs (Douglas and Lawson, 1997, 1998; Fugiel et al., 2017; Gustin et al., 2003; Kesler et al., 2015; Naredo, 2015b; Ndlovu et al., 2017; Norgate and Lovel, 2004; Warhurst, 1992; Young, 1992) which cannot be dissociated from major social conflicts (Martinez-Alier, 2002). Ignoring these costs also represents a market failure (Farzin, 1996; Lahn and Stevens, 2014), as does a private discount rate higher than the social one or uncertainty about the future (Brannlund et al., 2005). The increasing financialization of the economy where speculative movements on NRRs are remarkable also importantly distorts the market (Blas and Farchy, 2022; Carpintero and Naredo, 2018).

However, market imperfections are not the only factors affecting the ability of NRR prices as absolute scarcity indicators. Price components also suffer from serious limitations in reflecting physical scarcity. Indeed, marginal extraction costs are not only determined by mineral resource geological constraints but also by technological progress (Barnett and Morse, 1963; Solow, 1974, 1991, 1997). While depletion is expected to influence costs over time putting upward pressure on prices (Daly and Farley, 2011; Hanley et al., 2007; Pearce et al., 1990),² technological advancements and innovations can contribute to diminishing marginal extraction costs, thus leading to negative price trends (Berck and Roberts, 1996; Johnson et al., 1980; Krautkraemer, 1998).³ And under decreasing prices, extraction will be stimulated as the profit-maximizing owner of a resource will not have incentives enough to leave it in the ground (Hotelling, 1931). In this context, Perman et al. (2003) warn us that the quantities or qualities of the resource could be declining seriously and provoke exhaustion after a period of prolonged falling prices due to sufficiently rapid technological progress. Declining extraction costs can indeed result in a loss of mineral resources along with an increased physical deterioration linked to energy and water consumption, tailings, and land use changes (Cleveland, 1991; Valero et al., 2014). Technological progress can also reduce marginal exploration and discovery costs leading to increased reserves and hence higher supplies and lower prices, thus further stimulating extraction. The gradually acquired information about where to find a resource and how to extract it, making it more accessible, can further put downward pressure on prices (Reynolds, 1999). Given that the higher the extraction, the higher the supplies and the lower the prices, incentives for exploration and development of substitutes can also be reduced (Dasgupta and Heal, 1979; Hotelling, 1931). Even worse, “developing substitutes requires technology, technological advance requires time, and the less warning we have of impending resource exhaustion, the less time there is to develop substitutes” (Daly and Farley, 2011).

Thus, the prices of NRRs do not seem to be good indicators of their increasing absolute scarcity (Cuddington, 2010; Henckens et al., 2016; Svedberg and Tilton, 2006), nor does even their scarcity rent. Indeed, there is no strong evidence that such a rent, considered the best indicator of scarcity (Hanley et al., 2007; Stollery, 1983), is increasing either

(Farzin, 1995; Halvorsen and Smith, 1991; Lasserre and Ouellette, 1991). The other way around, oblivious to the physical reality, NRR prices are not only too low, as they usually ignore mining-derived external costs, but can also show a decreasing trend because of technological progress along with many short-term fluctuations (Agbeyegbe, 1993; Ahrens and Sharma, 1997; Lee et al., 2006; Neumann and Erlei, 2014; Slade, 1988).⁴ The low weight of the (monetary) energy component in total mining operating costs (Poxleitner, 2022) despite mining being a very energy-intensive activity (Igogo et al., 2021) further complicates matters. Added to this is the fact that raw material prices typically represent only a small percentage of the cost of a final product (Menzie et al., 2005).⁵ Such a context feeds the belief that there are no relevant limits to the scarcity of NRRs, which stimulates their continued massive extraction. Even worse, the energy and material requirements due to energy transition-fueled obsolescence and new technologies (Hume and Sanderson, 2021; International Energy Agency (IEA), 2022; Kettle, 2021; Pommeret et al., 2022; Valero et al., 2018b; Valero et al., 2021a; Valero and Valero, 2015) and the speculative movements on NRRs (Blas and Farchy, 2022; Goetz et al., 2021; Zheng et al., 2022) accelerate the road to exhaustion through what has come to be called neoextractivism (Carpintero, 2005; Carpintero and Naredo, 2018).

In the meantime, the extraction of mineral resources has increased exponentially over the last decades (Henckens et al., 2019; Valero et al., 2021b) contradicting the principles of CE, which builds on conservation rather than extraction. If we are to mimic the biosphere’s circular model, we must go beyond Hartwick (1977)’s rule and adopt a strong sustainability perspective, thus avoiding the existing divorce between monetary and physical analyses. This article responds to Hicks (1946)’s call for prudent conduct in consumption and Solow (1992)’s demand for considering physical variables to estimate the right NRR shadow prices. So, we propose a methodology which builds on the use of an exergy-based indicator of absolute scarcity to create the much-needed taxonomy of mineral substances, that is, the abiotic raw materials obtained from resources extracted from mines after they have gone through a process of beneficiation, transport, smelting and refining, thus serving as the basis for manufacturing processes.⁶ Classifying and ranking mineral substances according to their absolute scarcity is a *sine qua non* to make more meaningful and thus more effective CE-oriented strategies. Importantly, this indicator will not only allow overcoming the limitations usually attributed to physical indicators as scarcity’s proxy measures such as minerals’ heterogeneous quality (Perman et al., 2003). Also heeding the teachings of Georgescu-Roegen (1971), it will transcend the usual mass-based approach to absolute scarcity warning that depletion is more about the loss of mineral quality than quantity. This is fundamental in a physical world governed by the Law of Entropy where ore grades decline over time along with exponentially increasing marginal extraction costs and mining’s environmental impacts. This indicator shows the growing energy efforts that will be required to obtain mineral substances (Menzie et al., 2005; Smith, 1979). Even more, beyond enabling the calibration of economic tools to ensure we move towards circularity, the indicator can also set the basis for

⁴ The evolution of metal prices on the London futures market shows how nickel, lithium and cobalt prices plummeted in 2023 after a wave of supply (<https://www.bloomberg.com/news/articles/2024-01-09/ev-batteries-plunge-in-lithium-nickel-and-cobalt-prices-is-killing-deals>, accessed on March 6, 2024).

⁵ A threefold price increase of a raw material may make an average product no more than about 10 % more expensive (Henckens et al., 2016).

⁶ Distinguishing between *mineral resources* and *mineral substances* is important in this article as the embodied exergies and the prices with which we will reason refer to mineral substances for final use and not to mineral resources. As abiotic raw materials being the basis for manufacturing processes, mineral substances do not usually correspond exactly to the pure elements of the Periodic Table, even if they are close to them and we use the nomenclature of the table to identify them.

² As a mineral deposit starts in the most profitable areas (Mew, 2024), a mining firm will tend to extract more accessible high-grade reserves before moving deeper underground to lower grade reserves or reserves which are less accessible (Hanley et al., 2007).

³ Norgaard (1990) even points out that, when we begin to exploit a new resource, very little is known about where the best fields are, thus questioning the fact that we move on to sources being more expensive to extract in the face of resource depletion.

designing depletion charges targeted at raising social awareness and putting upward pressure on prices well before reserves are exhausted. This is crucial when the price system is expected to reveal true scarcity only when reserves are close to depletion (Reynolds, 1999). Last, but not least, our methodology will also serve to analyze the behavior of mineral prices, thus providing new insights into how they are formed.

Our analysis is intended to serve as a catalyst to stimulate recovery and recycling while preventing or curbing new extractive activities and waste generation, thus moving the focus from extraction to conservation. In so doing, it will also add to an emerging literature concerned with designing effective CE-oriented strategies (Arruda et al., 2021; Castillo-Díaz et al., 2024; Fitch-Roy et al., 2021; Ignatyeva et al., 2021). To this aim, the paper is structured as follows. The next section presents the exergy-based indicator on which our methodology builds and discusses the role of physical costs in assessing the absolute scarcity of mineral substances. It also revolves around how this indicator can be used to design economic tools for conservation. Section 3 measures the absolute scarcity of a list of mineral substances to create their much-needed scarcity-based taxonomy. It also shows the usefulness of our methodology for analyzing mineral price behavior and examines the policy implications of a mass-based approach to absolute scarcity. A note on the wrong focus on monetary flows rather than physical stocks makes up Section 4, while a note on the need to properly look at the signals of the biosphere's circular model constitutes Section 5. A Conclusions section ends the paper.

2. An economist's guide to sustainable mineral management

The voracious appetite for minerals of industrial nations has dangerous ecological implications (Young, 1992). Their actual exponentially growing consumption (Valero and Valero, 2015) is leading to the depletion of mineral reserves along with an exponentially increasing global environmental degradation which today's civilization is on track to push to the limit. A tonnage moved by mankind far greater than that moved by the planetary geological forces has changed the Earth's crust (Cendrero et al., 2005), thus giving rise to the concept of Anthropocene (Steffen et al., 2007). For over a century, mankind has depleted almost 30 % of the world's mineral reserves, with mercury, silver, gold, tin, and arsenic being the most depleted resources (Valero and Valero, 2010). Between 1984 and 2022, the annual extraction of metallic minerals rose by a factor of 3.3 whilst that of both industrial minerals and fossil fuels almost doubled (Fig. 1a and b).⁷

Mineral conservation then becomes a priority task especially when it comes to mineral resources whose extraction has recently increased dramatically due to their role in the energy transition and development of new technologies (Valero et al., 2021b).⁸ Even more, mineral resources must be extracted, concentrated, and refined in energy-intensive and polluting processes causing huge socioecological impacts.

2.1. The role of physical costs in assessing the absolute scarcity of mineral substances

In a physical world governed by the Law of Entropy where ore grades decline over time, concentration, chemical composition, hardness, and accessibility of mineral resources are key scarcity-determining factors. Thus when it comes to examining the absolute scarcity of mineral substances, we need to consider two types of exergy-based physical costs. To

calculate these costs, we must compare the current state of the mineral resources at stake to a hypothetical reference state where these resources are assumed to have been completely dissipated. The reference state considered for our analysis will be the one originally proposed by Valero (1998) and Naredo and Valero (1999), which was further developed and called "Thanatia" by Valero and Valero (2015).⁹

2.1.1. Exergy as a key concept for the analysis of mineral deposits

Concentration is the most important defining feature of mineral resources. This makes exergy, or quality energy, a more appropriate concept than the concept of just "energy" for ore deposit analysis since exergy depends on the ore grade.¹⁰ For this paper, we define exergy as the minimum amount of work (measured in kWh) required to obtain a mineral resource from a given reference environment called dead state or, in mining terms, depletion state (DS). In DS, it is assumed that the resource either cannot be extracted under certain economic and/or technological conditions or is dispersed and therefore has no exergy. So, the higher the ore grade, the higher the energy needed to replenish the resource at its current mine concentration from DS.¹¹ Exergy indicates the quality, usable energy contained in the resource. Therefore, mineral deposits are high-valued exergy resources that are physically separated from their surrounding environment, thus having a different chemical composition and a higher concentration and grindability (Valero and Valero, 2018a). Equivalently, mineral deposits are natural rarities offering concentrations of certain substances at levels far above the average in the Earth's crust, and as such they are finite resource stocks. Extraction and use of mineral resources then lead to their dispersion throughout the crust and hence the depletion of mineral reserves.

2.1.2. The exergy costs of mineral substances

The exergy cost of a mineral substance is defined as the actual exergy consumption for its mining, beneficiation, transport, smelting and refining. It also includes the energy required for the use of water and reagents, transport, environmental regeneration, and any other direct physical cost involved in the mining process. This cost, referred to as Embodied Exergy (EE) represents the exergy-based life cycle cost incurred from extraction of the mineral resource to obtaining the mineral substance for final use.¹²

2.1.3. The Exergy Replacement Cost as the shadow cost of mineral resource depletion

The shadow cost of a mineral resource's depletion can be estimated

⁹ A detailed description of these costs as well as their mathematical formulation can be found in Valero and Valero (2015).

¹⁰ There are two more reasons explaining the appropriateness of the concept of exergy: i) in any mixture of substances, it is exergy and not energy that is lost; ii) when separating two components of a mixture, the energy required must be distributed in proportion to the thermodynamic value of the separated substances, and this value is quantified through exergy. The relationship between exergy and entropy is given by the fact that the exergy lost in all irreversible physical processes is equal to the ambient temperature multiplied by the entropy generated in the process.

¹¹ The exergy of an ore deposit links to both its concentration and its chemical composition. Accordingly, its concentration exergy increases with its ore grade, while its chemical exergy is usually very low thus explaining the very low reactivity of mineral resources (i.e. the chemical exergy of gold is only around 300 kJ/kg (Valero et al., 2018c)). Unlike fossil fuels (with a high chemical exergy being almost equal to their High Heating Value -or energy content- i.e. over 40,000 kJ/kg for oil or natural gas) and except for sulphides and some other anions (with a medium reactivity), oxides, silicates, carbonates, sulphates, and other salts are quite stable.

¹² As exergy can also be viewed as the minimum extraction cost to obtain a resource at its current mine concentration from a given DS, the difference between the EE and the resource's exergy can show the huge physical irreversible losses involved in mining processes.

⁷ Mineral resources are distinguished from fossil fuels and broadly classified into metallic and non-metallic (or industrial) resources.

⁸ Originally, the metabolism of the industrial civilization was based mainly on the use of abundant and generally well distributed materials in the Earth's crust (coal, iron, water, ...). In contrast, today's society is increasingly and exponentially demanding resources that are scarcer and poorly distributed territorially.

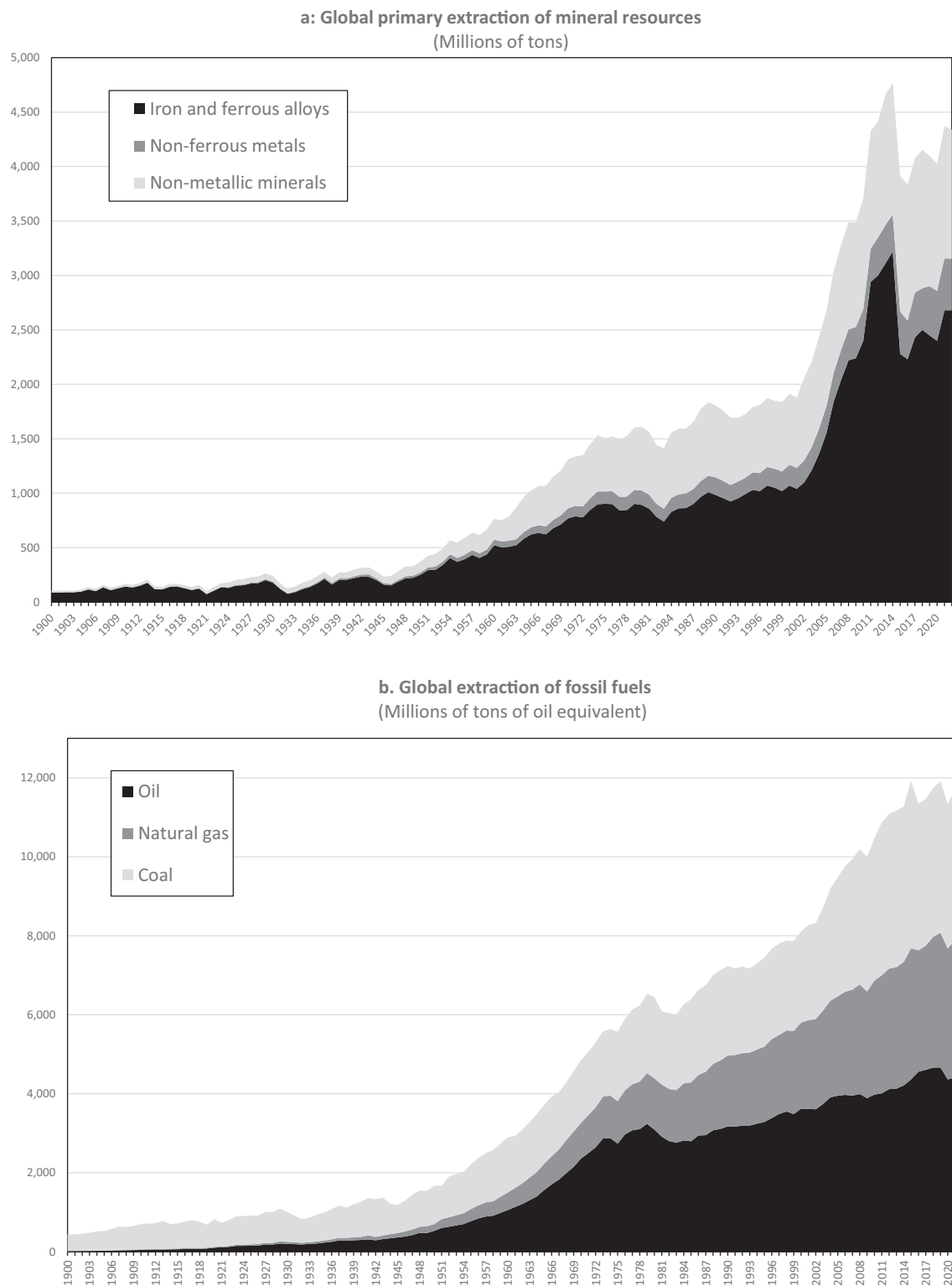


Fig. 1. Global extraction of non-renewable resources from 1900 to 2022

through the concept of Exergy Replacement Cost (ERC). It can be defined as the hypothetical exergy cost we would incur if we were to obtain the ore at its current mine concentration and composition from a previously defined DS using the best available technology (Valero et al., 2021b; Valero and Valero, 2019). It can then be viewed as the avoided cost for keeping the resource in the ground at its actual mine conditions rather than dispersed throughout the Earth's crust. So it informs about the social cost of extracting and using a mineral resource or,

equivalently, about its shadow cost of depletion. The less abundant a resource is in quantitative terms (involving its higher dispersion with extraction/use as there would be a lower amount of mineral content in the crust) and the higher its mine concentration, the greater its ERC, thus the more careful humanity should be with its uses.

In this context, we observe that, under decreasing ore grades over time, the shadow costs of depletion (ERC) will progressively materialize in the form of increasing real costs (EE). So the ERC can also be defined

as the ultimate exergy cost of mining with the prevailing technology once a mineral reserve has reached a specific depletion level. Even more, it warns us that, in a physical world governed by the Law of Entropy, the above-mentioned transformation of shadow costs into real costs will present an exponentially increasing trend. The concentrations found in mineral deposits are usually very low, in the order of $10^{-1}, 10^{-2}, \dots, 10^{-n}$. If a mine with an initial ore grade of 10^{-n} kg ore/kg rock is mined to a concentration 10 times lower, the exergy needed to extract the same ore amount increases at least by a factor of 10 (Valero and Valero, 2015). Then the ERC gives us an idea of how quickly we can reach exhaustion of mineral reserves.

2.1.4. The Thermodynamic Rarity of mineral substances: an accurate indicator of absolute scarcity

Against the usual mass-based approach to absolute scarcity, our exergy-based indicator warns us that depletion has more to do with the quality of mineral resources than the quantity of mineral substances or elements contained in the Earth crust.¹³ Absolute scarcity has to do with the limited number of mineral deposits containing the resource at the specific mine conditions making it economically, ecologically, and socially exploitable. Even more, as rarities of the Earth's crust where the concentration of the desirable mineral resource is usually inversely proportional to its tonnage (Chapman and Roberts, 1983; Ortiz, 1993), ore deposits with higher grade content tend to be quantitatively scarcer. In this context, and given that ERCs are gradually becoming real EEs, it is necessary to take the Thermodynamic Rarity (TR) into account when assessing absolute scarcity. As a synthetic indicator defined as the sum of ERC and EE, the TR not only informs on the total physical costs of mineral substances but also remains unchanged over time under a given technology. Accordingly, as ore grades decline, we would only observe a shift of the ERC and EE boundaries (with ERCs decreasing and EEs increasing) shown in Fig. 2, which represents the TR for a given point in time and a given mineral substance at all stages of the process to obtain it.

The TR informs on the thermodynamic value of mineral substances, thus assigning a higher value to those requiring higher energy efforts to obtain regardless of their absolute mass or the mass of the corresponding elements in the Earth's crust.¹⁴

2.1.5. "Thanatia" as the dead state

As earlier stated, we use "Thanatia" as DS for our analysis. It represents a hypothetical state towards which the exponentially increasing human-induced degradation moves planet Earth. It involves a hypothetical state of maximum entropy of the minerals in the upper continental crust where all mineral resources have been homogeneously dispersed throughout the crust and all fossil fuels have been burnt or otherwise used up. Hence, it consists of a continental crust with plenty of common rocks without any mineral deposits and with an atmosphere full of CO₂ and a hydrosphere only composed of saline waters at standard ocean concentration. Its chemical composition corresponds to a state of minimal mineral concentration equating to that of the average upper crust where extraction costs would be maximum (Henckens et al., 2016).¹⁵ "Thanatia" is then the hypothetical state of absolute depletion of the planet's mineral deposits, a condition that cannot be reversed on a human timescale. This means that it is not discretionary in nature or, in

other words, it does not depend on economic and technological factors and is therefore invariable in time for each mineral resource. Undoubtedly, this makes "Thanatia" the most appropriate DS to consider for the analysis of the absolute scarcity of mineral substances.

2.2. Economic tools for mineral conservation based on "Thanatia" as DS

As they inform about the shadow costs of depletion, the ERCs allow designing depletion charges proportional to them which can serve to raise social awareness and put upward pressure on prices well before mineral reserves are exhausted. Calculated by taking "Thanatia" as DS, they give an idea of the 'effort' that nature made to concentrate mineral resources from a completely dispersed state to their current concentration in deposits (Valero and Valero, 2018a). So these ERCs can be viewed as a *bonus* nature offers us for free, thus acting as a psychological barrier to further deliberate destruction (Valero and Valero, 2019). This is especially true if we consider that these shadow costs progressively become real exponentially increasing EEs.

On the other side, the TR could be used to create a taxonomy for mineral substances based on their degree of absolute scarcity. Such a taxonomy is a *sine qua non* to properly order the material world,¹⁶ which is in turn a precondition to design effective mineral governance mechanisms. It could serve to calibrate economic tools aimed at contributing to moving our economies towards circularity. Even more, it could help to direct effectively the investment of the money collected from ERC-based depletion charges into research aimed at primarily two objectives: i) facilitating the search for substitutes for the more physically costly mineral substances, and ii) making the use and recycling of these latter more efficient. This could fill the existing gap in research oriented to ensure the supply of raw materials for future generations denounced by Schmidt (2019).

3. Creating a taxonomy built on the absolute scarcity of mineral substances

We analyze 39 mineral substances including metallic and non-metallic substances.¹⁷ To calculate their ERCs and EEs, we assume that the technology used in the mining process going from extraction to pre-smelting/refining is the same as that used to bring the mineral resource from "Thanatia" to the mine. In other words, the technology applied for the entire range of concentrations between the ore grade in the mine and the pre-smelting grade (from X_M to X_B in Fig. 2) is the same as that applied for the range going from the dispersed state found in "Thanatia" to that in the mine (from X_C to X_M in Fig. 2). If technology does not change, the TR of a given mineral substance will remain constant during the whole mining process, since it depends on fixed initial ("Thanatia") and final (the commodity's quality following beneficiation, which is usually commercially imposed) states. Accordingly, and based on various literature sources (Chapman and Roberts, 1983; Mudd, 2007a, 2007b, 2010; Norgate and Haque, 2010; Norgate and Jahan-shahi, 2010, 2011), we quantify the energy amount needed to mine and beneficiate the mineral substances.¹⁸

Once we have calculated the ERCs and TRs, we first rank the mineral substances according to the physical shadow costs of depletion of the resource from which they are obtained (Fig. 3).¹⁹ The results indicate

¹³ The case of water evidences it clearly: while it is very abundant on Earth, water of a quality suitable for drinking, irrigation, etc. is very scarce. The fact that many mines are closed when the best seams are exhausted and reopen when technology and/or market prices make viable again their exploitation well exemplifies this too.

¹⁴ This is the case of silicon semiconductors, rare earths or platinum group metals which are very energy costly to isolate and refine.

¹⁵ See Valero and Valero, 2015 for a comprehensive description of "Thanatia" as the DS.

¹⁶ Ordering the material world requires knowledge of the scarcity of mineral substances, their exergy, and the Gibbs' free energy they contain marking the possibilities of their chemical manipulation (Naredo, 2015a).

¹⁷ Appendix A reports the list of the analyzed substances along with their ERC and TR values, as well as their prices for 2000 and 2015.

¹⁸ See Valero and Valero, 2015 for further information about the calculation of the ERCs and TRs.

¹⁹ The values of all the graphs in Section 3 are in logarithmic scale to facilitate comparison of mineral substances.

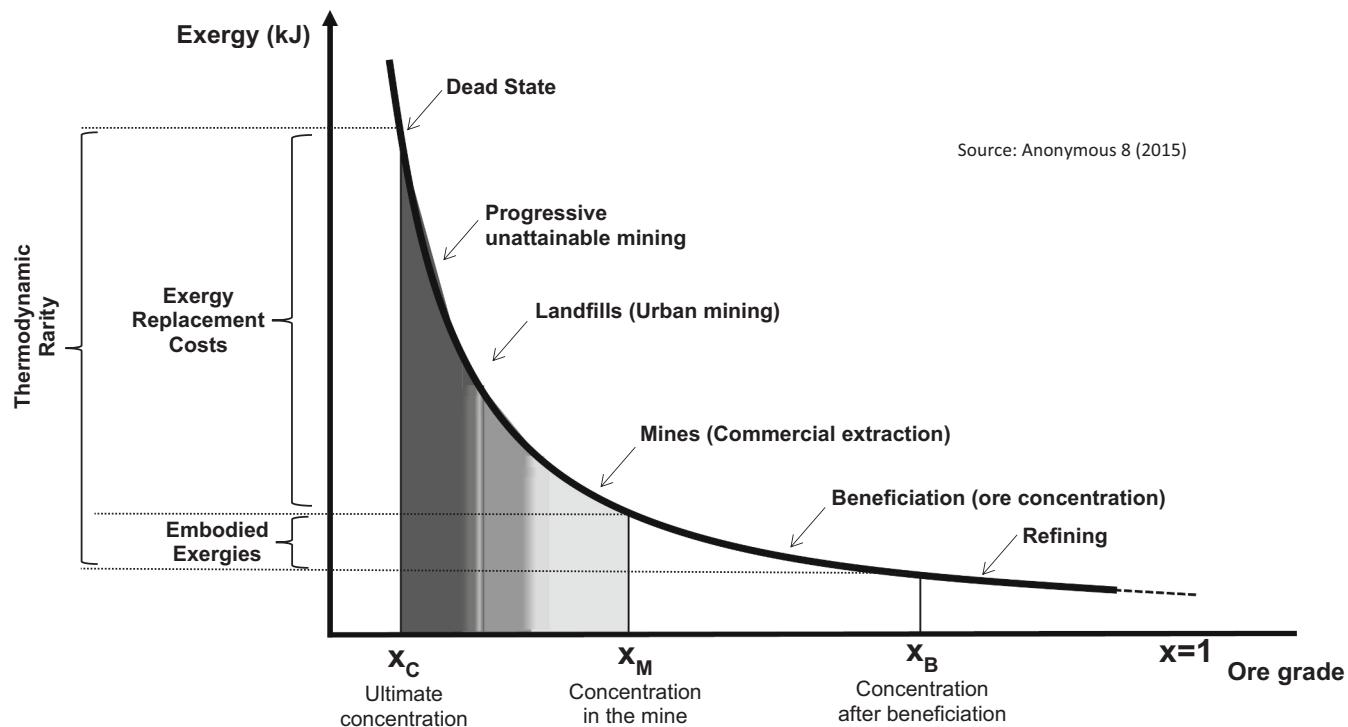


Fig. 2. Relationship between physical costs and ore grades.

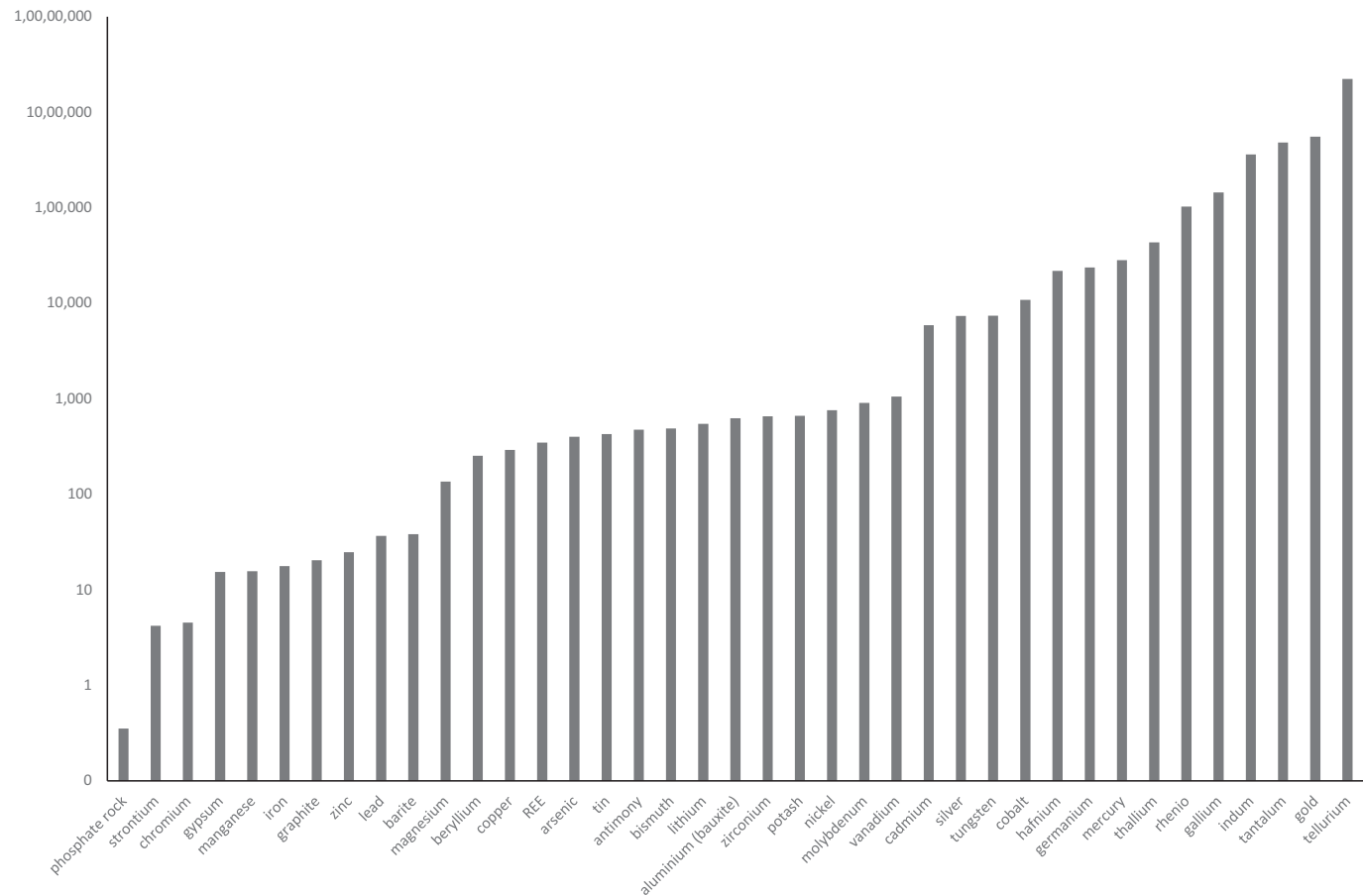


Fig. 3. Ranking of mineral substances according to the Exergy Replacement Costs (values in GJ/t)

that the ERCs range from 0.35 GJ/t (phosphate rock) to 2,235,698.9 GJ/t (tellurium). For a fourth of substances (25,6 %), the ERC is lower than 38.34 GJ/t, while for rhenium, gallium, indium, tantalum, gold, and tellurium (15,4 %) the shadow depletion costs are between 294 (rhenium) and 6387.7 (tellurium) times higher than those for the phosphate rock,²⁰ thus these latter substances becoming of special attention.

Second, we add the EEs to the ERCs to calculate the TRs which will allow us to create the absolute scarcity-based taxonomy of mineral substances. In doing so, we observe that the ranking change a little bit compared to that reported in Fig. 3. Indeed, those substances for which the EEs have a higher weight over the TR than the ERC become of more special attention now as shown by Fig. 4. That is, they climb a few positions in the ranking, thus showing that the mine conditions that make them physically costly to extract from the mine play an important role in explaining their absolute scarcity. So, for instance, while, in ascending order, the highest ERCs correspond to rhenium, gallium, indium, tantalum, gold, and tellurium, the absolute scarcity-based taxonomy shows us that the *rarest* substances are, from least to rarest, rhenium, indium, tantalum, gold, gallium and tellurium, with TR values ranging from 103,087.44 GJ/t to 2,825,104.16 GJ/t.

3.1. New insights into mineral price formation

Our analysis not only gives further evidence of the random behavior of prices for mineral substances. By plotting the correlation between absolute scarcity and prices, it also more accurately shows that markets do not provide an advance of exhaustion of rare mineral substances, thus enriching knowledge. For the years 2000 and 2015, Fig. 5 plots the poor correlation between the TR and prices of the rarest mineral substances (those placed to the right of beryllium in Fig. 4). Note that such a correlation is even lower when considering 2015 prices (0.0162 vs. 0.0179) despite the continued exponential extraction of mineral resources during the analyzed 15-year period (see Fig. 1a).

Even more, by measuring the absolute scarcity through the TR, our results provide two important insights into the study of mineral price formation. Firstly, they show that the extraction costs (included in the EEs) play a less significant role in determining the prices for mineral substances than that assumed by conventional economics despite mining being very energy intensive. The correlation between the TRs and 2000 prices for the 39 substances is lower than that between the ERCs and 2000 prices (0.0359 vs. 0.0396), thus prices adjusting worse when considering the total physical costs. Fig. 6 helps to show this for the rarest substances when compared to Fig. 5: for the year 2000 the correlation drops by 16.3 % when adding the EEs to the ERCs (from 0.0214 to 0.0179), the fall being 26.36 % in 2015 (from 0.022 to 0.0162).

Secondly, and as shown by Fig. 4, our results indicate the relevance of ERCs in determining scarcity. This implicitly points to the need to design ERC-based economic tools to raise social awareness about scarcity and put upward pressure on prices well before mineral reserves are exhausted. Interestingly, as the ERCs are shadow costs which progressively and exponentially convert into real EEs, their relevance in determining scarcity suggests that the EEs can also be viewed as a measure of *perceived rarity*. Overall, and aligned with Solow's advice, our results call for considering physical indicators when it comes to sustainable mineral resource management.

3.2. The risky policy implications of a mass-based approach to absolute scarcity

Adopting a mass-based approach to scarcity when seeking the more

sustainable management of mineral resources can paradoxically contribute to accelerating the road to exhaustion. Such an approach can divert attention from resources whose extraction should be stopped or significantly reduced. Henckens et al. (2016) is a good example of this. These authors consider as 'not scarce' mineral substances which are very rare such as cobalt, zirconium, lithium, indium, tantalum, vanadium, germanium, mercury, gallium, and thallium (Table 1).²¹ Their look at absolute scarcity from a mass perspective leads them to forecast exhaustion times between 2000 and 1000,000 years after 2050 for these substances, thus feeding the belief that there are no relevant limits to their physical scarcity. However, the way they consider availability borders on tautology. Since the mass of the Earth's upper continental crust is equal to 2.77×10^{22} kg (Yoder, 1995) and ore concentrations are of the order of 10^{-1} kg ore/kg rock, abundance of these substances or elements in quantitative terms is an easily expected result thus making meaningless the adoption of a mass-based approach.²²

Besides, ignoring that depletion has more to do with the quality of mineral resources than with the quantity of mineral substances or elements in the Earth's crust can also contribute to managing unsustainably mineral substances which both a mass and an exergy-based approach consider of special attention. This is the case for gold, rhenium, silver, tungsten, cadmium, molybdenum, and nickel. Indeed, as a mass-based approach ignores the role of mineral quality in explaining mineral resource depletion, it overlooks the fact that prices take into account neither the physical depletion costs of mineral resources nor the fact that these shadow costs will progressively and exponentially convert into real EEs. It also ignores the limited role of EEs in determining the prices of mineral substances. Thus, although a mass-based approach allows for evidence of the poor correlation between mineral prices and absolute scarcity (Henckens et al., 2016), it prevents researchers from understanding the underlying causes of this poor correlation. This makes them rely on the price mechanism when designing tools for mineral management. So, they may riskily recommend market-based tools (Henckens et al., 2019) that actually stimulate extraction over conservation, accelerating the course towards exhaustion of mineral reserves.

4. Mineral production? The wrong focus on monetary resource flows

As mineral economists use the conceptual tools and principles of standard economics (Gordon and Tilton, 2008), the economic analysis of NRRs builds on a monetary approach that seriously compromises their sustainable management. Economists usually work on monetary flows of mineral resource "production" that can be accumulated or de-accumulated at will without any physical cost. Hence, they speak of gold "production", copper "production", etc., and sum "added values" of mining to those of other productive activities ignoring that mining is a purely extractive activity. Their monetary approach allows them to work on assumed renewable mineral supply and demand flows supposed to lead to equilibrium price formation. Considering that mineral resources are unlimited as there will always be new discoveries and/or existing resources will be replaced by new ones at no additional cost is a

²¹ While Henckens (2021) further analyzes the scarcity of mineral substances, he focuses on a much lower number of substances than Henckens et al. (2016). This is why we focus on this latter. However, it is worth noting that both papers draw similar conclusions in terms of substances requiring special attention except for iron, lead and arsenic, which, in contrast to Henckens et al. (2016), Henckens (2021) considers of not special concern, and indium, which Henckens (2021) considers scarce.

²² Take for instance the case of cobalt. As its concentration is equal to 10^{-5} kg/kg of crust, its endowment would be equal to 10^{17} kg ($10^{22} \times 10^{-5}$). Considering that the amount extracted during 2022 was equal to $1.97 \cdot 10^8$ kg (National Minerals Information Center, 2024), such an endowment would ensure its availability for millions of years.

²⁰ Note that, despite the low ERC, the phosphate rock is still of special attention because plants can only absorb phosphorus, a vital element for nature's biogeochemical cycles, in the presence of certain microorganisms.

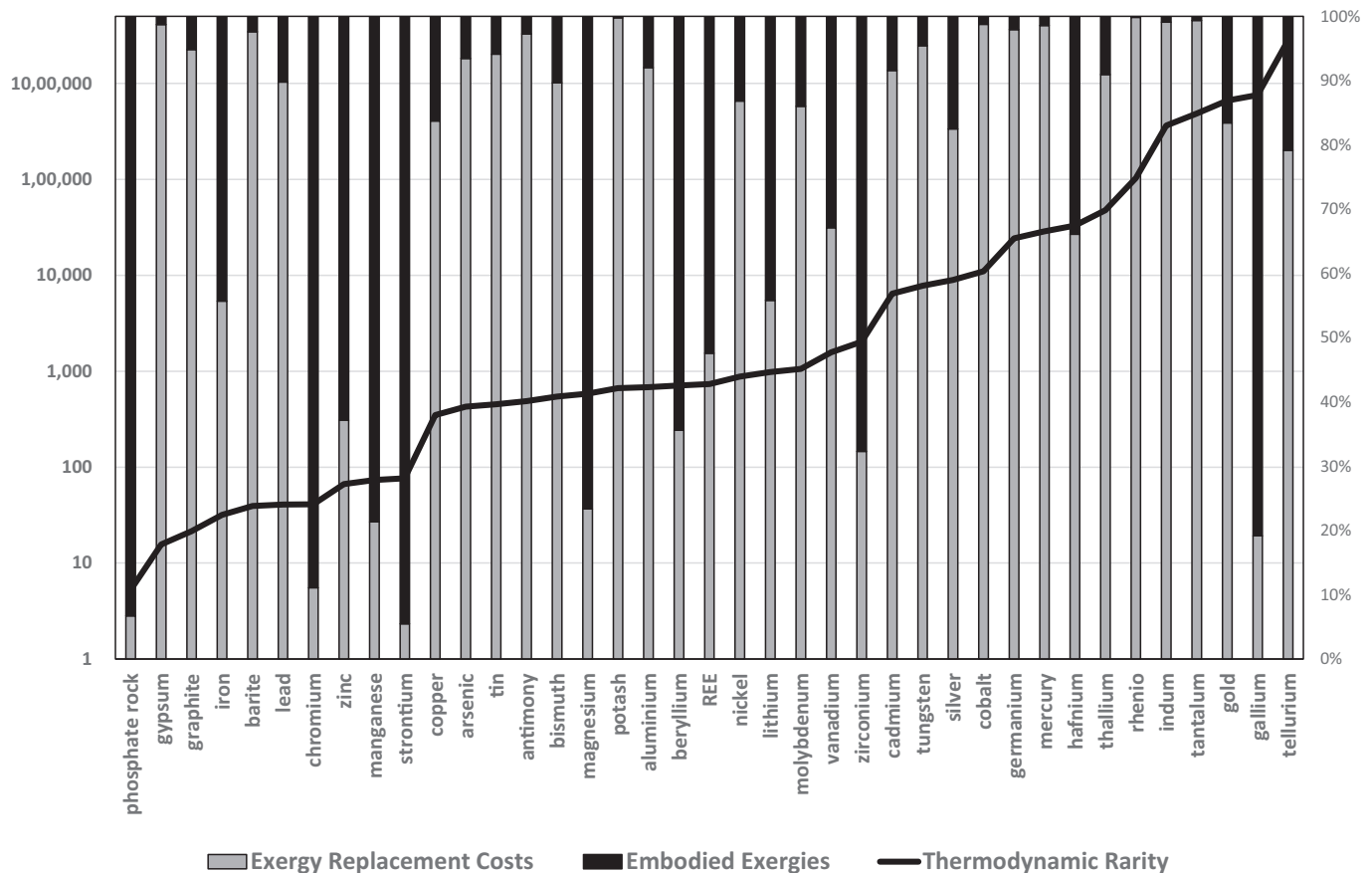


Fig. 4. Ranking of mineral substances according to their Thermodynamic Rarity (TR) along with information about the Embodied Exergies/Exergy Replacement Costs weights over TR (values in GJ/t)

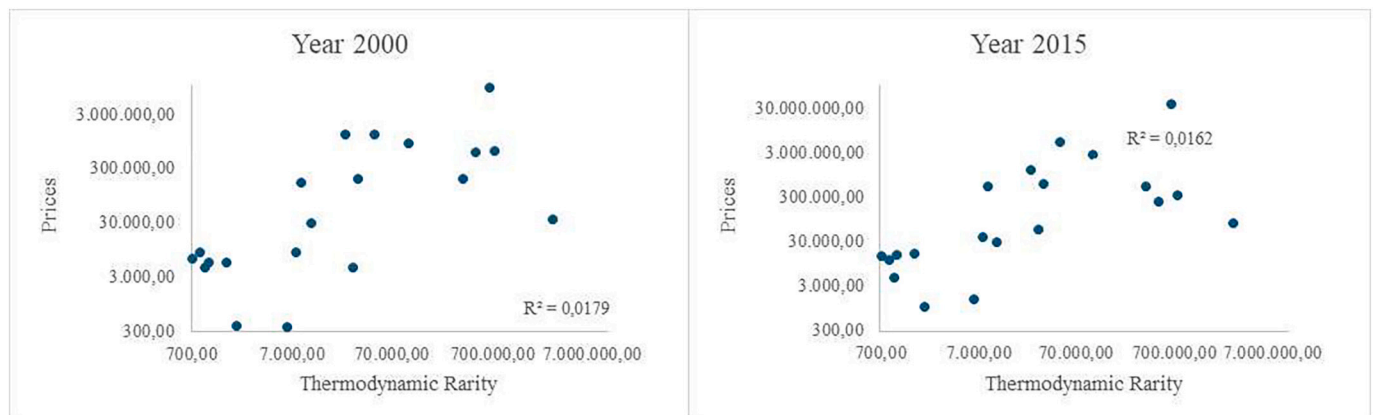


Fig. 5. Relationship between Thermodynamic Rarity and Prices for the rarest substances

key assumption of these monetary analyses. Based on Hotelling (1931)'s seminal work, and under arbitrarily specified discount rates, economists usually formulate optimal inter-temporal allocations of monetarily valued resource stocks.

However, when the supply is made up of non-renewable physical stocks, equilibrium price formation is an impossible task because prices not only ignore the physical costs of depletion. They also ignore that these shadow costs will progressively transmute into exponentially increasing real costs.

5. A note on the biosphere's circular model

Seeking to close the material cycles is an important step to move our economies towards circularity. However, in so doing, it is crucial to look at *all* the signals of the biosphere's circular model. This model shows that the conversion of waste into resources is possible through both solar energy (and its derivatives) and symbiotic processes occurring in nature stimulated by biological diversity. Even more, through photosynthesis, the biosphere's age-old functioning teaches us that a system's sustainability mainly depends on the use of both an inexhaustible source of energy (which is key for recycling) and the use of abundant materials. Let's take for instance the case of herbaceous plants. About 90 % of their

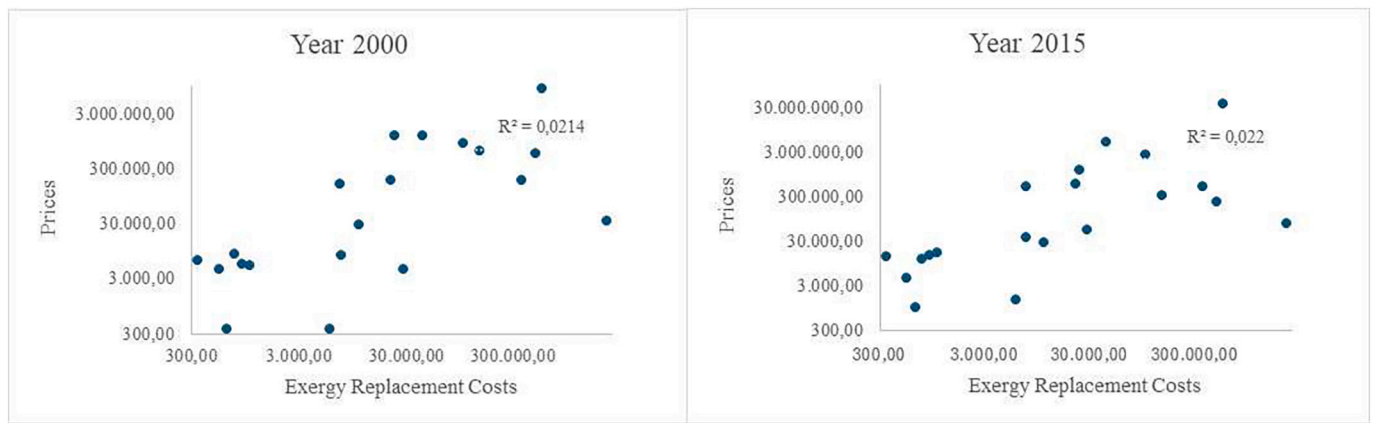


Fig. 6. Relationship between Exergy Replacement Costs and Prices for the rarest substances

Table 1

Scarcity of mineral substances according to an exergy-based and a mass-based approach^a.

Exergy-based approach		Mass-based approach			
Rarest substances (from rarest to least rare)	Thermodynamic Rarity (GJ/t)	From very to moderately scarce (< 1000 years)		Not scarce (≥ 1000 years)	
		Exhaustion period after 2050		Exhaustion period after 2050	
		Substances		Substances	
gallium	754,828.05	antimony	–10	barium	1000
gold	663,306.59	gold	10	cobalt	2000
tantalum	485,918.95	molybdenum	50	manganese	2000
indium	363,917.21	zinc	50	zirconium	2000
rhenium	103,087.44	rhenium	80	lithium	9000
thallium	47,789.82	copper	100	indium	10,000
mercury	28,707.00	bismuth	200	strontium	10,000
germanium	24,247.07	silver	200	aluminum	20,000
cobalt	11,010.12	tin	200	REE	20,000
silver	8937.59	chromium	200	tantalum	20,000
tungsten	7786.28	iron	300	vanadium	20,000
cadmium	6440.84	lead	300	magnesium	30,000
zirconium	2025.93	nickel	300	beryllium	200,000
vanadium	1572.30	tungsten	300	germanium	200,000
molybdenum	1055.91	arsenic	400	mercury	400,000
lithium	978.33	cadmium	500	gallium	1000,000
nickel	876.53			thallium	1000,000

^a Only substances that have been studied in both this article and Henckens et al. (2016) are compared.

Source: Adapted from Henckens et al. (2016)

fresh weight is made up of water, while 90 % of the remaining 10 % of dry matter is made up of carbon, hydrogen, and oxygen. This leaves only about 1 % of the total fresh weight made up of so-called macro- and micronutrients (which usually exist in the environment in quantities far more than what is required by the plants).

Our methodology warns us that we need to learn from the biosphere. Indeed, it shows us that our socioeconomic system, mostly built on the use of NRRs, can also reach sustainability if we increase the use of renewable resources while moving towards the use of abundant, recyclable, and easily obtainable mineral substances. This is luckily an achievable goal as long shown by past human societies which have put the biosphere's production at their service, artificializing it over millennia without undermining the resource base. But ecology also shows that a system's sustainability depends on its ability to adapt to new events about which the system's information pathways send data (Margalef, 1992). So, our methodology also points to the great problem with industrial civilization: it bases mineral resource management on *biased* monetary information as it only partially considers the physical extraction cost and ignores the physical ERCs of mineral resources. Worse, the industrial civilization blocks the pathways that inform on the physical aspects linked to mineral management, thus undermining the resilience of society and compromising sustainability. Our methodology

can then serve to pave the way to re-establish these pathways with relevant physical information (Fig. 7).

6. Conclusions

The long-standing debate on scarcity of NRRs and environmental impacts of mining has intensified during the last years due to the exponentially growing global demand for mineral substances. Since the first calls for applying a conservation ethic almost half a century ago (NAS, 1975), interest in moving towards a more circular economy (CE) has recently gained ground at all governance levels. Aligned with research, policy packages have emerged setting out guidelines, recommendations, and codes of conduct for the reuse, repair, remanufacture and recycling of existing materials and products (De Pascale et al., 2023). In their quest to conserve minerals and avoid waste generation these packages emphasize the role of technology in achieving sustainability (Boryczko et al., 2014).

However, these packages often rely on the current price system as the best social mechanism for allocating mineral resources efficiently, even though economists have long recognized that their prices are poor indicators of absolute scarcity. Besides, a mass-based approach to physical scarcity predominates in the existing research analyses. This leads these

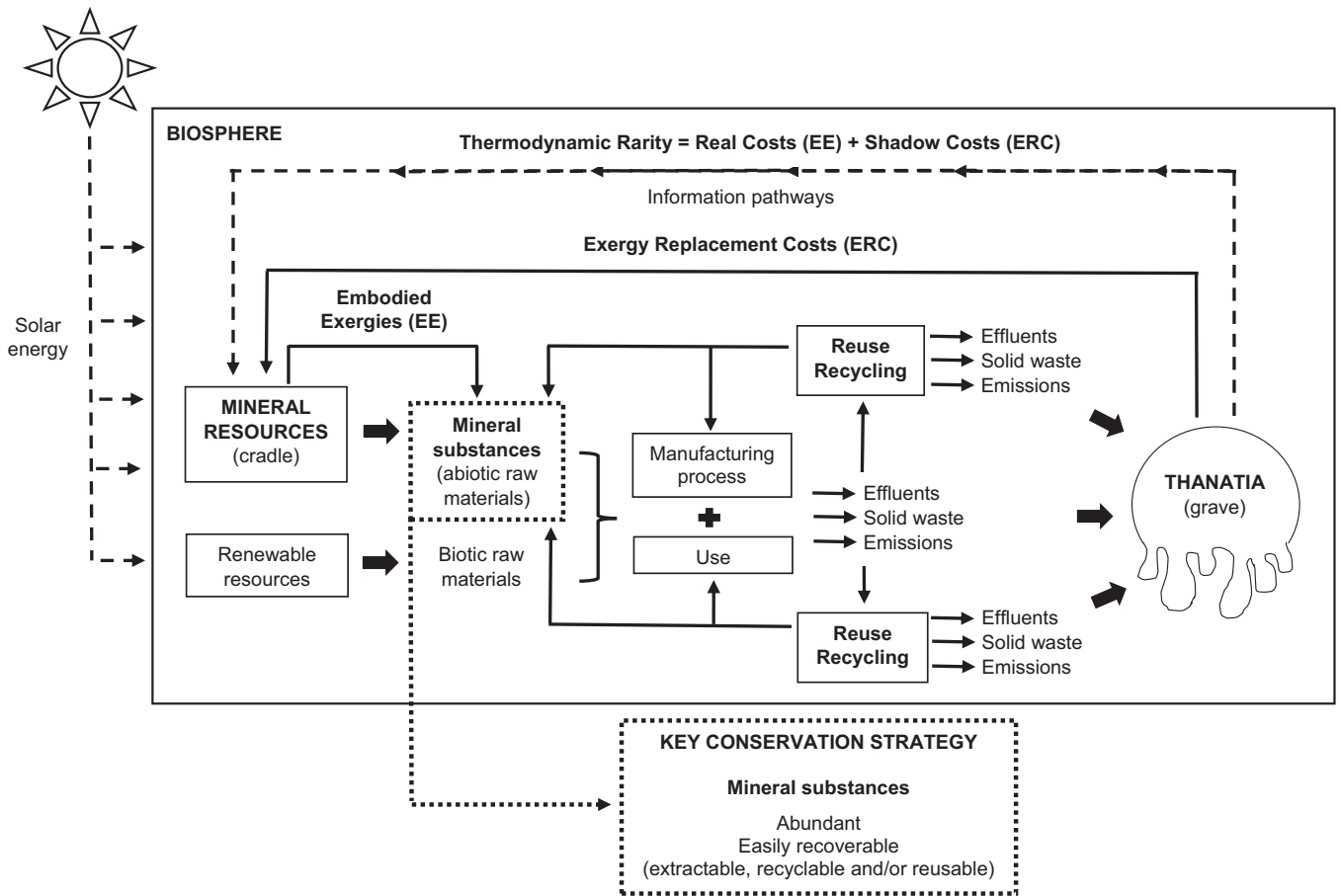


Fig. 7. Well-informed mineral resource management for sustainability.

studies to consider as not scarce mineral substances which, although being found in huge amounts in the Earth crust, are physically costly to obtain and hence should also be of special attention. As discussed in this paper, depletion has more to do with the quality of mineral resources than the quantity of mineral substances or elements contained in the Earth crust. In a physical world governed by the Law of Entropy where ore grades decline over time with exponentially growing mining's energy requirements and socioecological impacts, concentration, chemical composition, hardness, and accessibility of mineral resources are key scarcity-determining factors. The institutional tendency to view criticality of raw materials as the potential risks associated with their supply in an increasingly complex geopolitical context (Grohol and Veeh, 2023; National Science and Technology Council (NSTC), 2016; National Science and Technology Council (NSTC), 2018; Schulz, 2017) makes matters worse. Mineral deposits are natural rarities offering concentrations of certain substances at levels far above the average in the crust. As such they are finite resource stocks. So it is their availability under certain physical conditions rather than supply's geopolitical risks what should determine the criticality of mineral substances. CE-oriented policy packages ignoring all this can paradoxically accelerate the road to exhaustion.

The methodology we propose can help to resolve the crossroads we are at. To this aim, it offers an accurate indicator of the absolute scarcity of mineral substances: the Thermodynamic Rarity (TR). Transcending the usual mass-based approach to scarcity, it informs about the thermodynamic value of mineral substances, thus assigning a higher value to those requiring higher energy efforts to obtain regardless of their mass in the Earth crust. Obtained as the sum of the Exergy Replacement Costs (ERC) and the Embodied Exergies (EE), which we calculate considering "Thanatia" as the dead state (DS) (the hypothetical state of absolute

depletion of the planet's mineral deposits), the TR provides insights into the shadow (physical) costs of depletion of mineral resources and the real (physical) costs incurred from extraction to obtaining the mineral substances, respectively. Thus, it informs about the total physical costs of these substances and warns us that the shadow costs of depletion will progressively materialize over time in the form of exponentially increasing real costs of extraction, concentration, smelting and refining. Although determining how far from "Thanatia" the current depletion state of each mineral resource (the ore deposit's current economic and technological barrier) is would certainly be policy relevant,²³ so is having calculated the TR taking "Thanatia" as DS. Indeed, this TR enables creating an absolute scarcity-based taxonomy of mineral substances which is crucial for designing CE-oriented strategies when price arbitrariness becomes a market barrier to their effective implementation. A barrier further confirmed by our results, which not only more accurately show that markets do not provide an advance of exhaustion of rare mineral substances, thus enriching knowledge. They also show

²³ Indeed, in some cases the DS of mineral substances may be close to "Thanatia" and, in others, far removed from it. For example, in the case of drinking water obtained from seawater desalination, we have a resource with an absolute DS that coincides with "Thanatia". Despite this, it is still available on a large scale. Another example is lithium, which would first be extracted from silicates with high lithium content, such as spodumene or salt flats. Once these were depleted, it could be obtained from low-lithium silicates, with increasing physical and financial costs. If the silicates were also depleted, lithium could be obtained from seawater in tropical areas, where higher salinity levels prevail, but at such extreme physical and monetary costs that most current uses would be unfeasible. The latter scenario would represent "Thanatia", or the absolute DS of lithium.

that the extraction costs (included in the EEs) play a less significant role in determining mineral prices than that assumed by conventional economics. In this context, the taxonomy can serve to calibrate economic conservation tools to ensure they indeed contribute to move us towards circularity. Designing depletion charges for ore deposits being proportional to the shadow costs of depletion of mineral resources would therefore be useful in raising social awareness and increasing mineral prices well before reserves are exhausted. This is especially true when the ERC appears as the most important TR-determining component, as also shown by our results.

Accordingly, our methodology responds to the urgent need to consider depletion of mineral resources, as long advocated for by economists (El Serafy, 1989, 2013; Jevons, 1866). But that's not all. By calling for physical costs to be looked at long before it is too late, it also calls for the convergence of weak and strong sustainability approaches towards the same integrated purpose. If a given technological and/or economic barrier was chosen as the DS instead of "Thanatia" for the calculation of the ERCs of mineral resources, an exergy-based indicator of the relative scarcity of mineral substances could also be obtained. In the face of the irreversible depletion of mineral reserves, this also becomes an interesting issue for further research. The ERCs associated with different technological and/or economic barriers could be calculated, thus making it possible to design monetary tools allowing for the gradual amortization of the ore deposits and hence serving to further raise social awareness and put upward pressure on prices. When it comes to sustainable mineral management, dialogue between environmental and ecological economists is as relevant as interdisciplinary collaboration. The discussion about scarcity and impacts of mining is more important than ever and, as Schmidt (2019) reminds us, this time "must lead to a result and must not get stuck in different schools of thought as it did 40 years ago". Even more, our methodology not only allows comparing mineral substances while considering their chemical differences, thus overcoming the limitations usually attributed to physical indicators as scarcity's proxy measures. It also enables making comparative analyses between countries (Valero et al., 2021b) facilitating global cooperation for mineral governance and setting the basis for the creation of an international institution on Mineral Resource Management as some authors have already called for (Henckens et al., 2019). Indeed, as exergy evaluates matter and energy into a unified concept, the TR represents a universal and stable measurement unit (Finnveden et al., 2016) which is only constrained by current mining technology and geological knowledge of the Earth crust (Valero and Valero, 2022). It can then provide an unambiguous physical cost map independent from spatial-temporal arbitrariness, thus contributing to more informed decision-making at the planetary level.

Today, in a world that is hungry for mineral resources, whose demand is expected to be further stimulated by the "green economy", not only we must redouble the efforts to move towards circularity. We must separate aspirations from reality (Lehmann et al., 2023) and avoid trying to square the conservation circle through "optimal extraction" as suggested by current research (Hoogmartens et al., 2018). CE-oriented strategies should learn from the biosphere and hence promote the use of renewable resources and the use of abundant, recyclable, and physically easily obtainable mineral substances. Sustainability can be reached if we prioritize, as the biosphere does, sufficiency and symbiosis rather than efficiency and competitive behaviors. The role of technology should also be considered in its rightful place (Valero and Valero, 2015). Picking the "low-hanging fruits" first believing that the rest can be left for the future with the hope that technology will reduce or offset the rising costs of obtaining mineral substances shows a society that is blind to the physical reality from which it cannot escape. The Law of Entropy imposes thermodynamic limits to efficiency gains and hence the substitutability of production factors due to exponentially growing energy requirements as mineral resources get depleted. The Second Law also dictates that perfect recycling in industrial processes is not possible. In each cycle, some quantity and quality of materials is unavoidably lost,

even making it impossible to close the first cycle (Valero et al., 2021a; Valero et al., 2021b; Valero and Valero, 2019). So making extraction cleaner, faster and cheaper (Haddad et al., 2023) is simply a myth. A myth that can be easily dismantled when considering the total physical costs of mineral substances. Worse, our society's voracious appetite for mineral resources exacerbates the technological flaw that originated with the industrial revolution: building a society on the extraction and depletion of mineral reserves with which to build a machine that demands (and allows for the extraction and depletion of) even more mineral reserves (Commoner, 1971).

So we can no longer delay the reconversion of the industrial civilization's metabolism if we are to keep us within the planetary boundaries to safeguard the global commons for all people now and into the future (Rockström et al., 2023). And a good first step in doing so is certainly to consider the total physical costs of mineral substances as calculated by our methodology. Until this happens, the rules of the economic game will continue to stimulate resource extraction and deterioration over recovery and reuse leading to global degradation, thus dragging us towards states of greater planetary entropy. These rules will keep pushing the Earth, which originated as a kind of *soup* from which life began to emerge in the seas, towards a kind of *crepuscular mush* whose chemical composition we have called "Thanatia". So we must act now. And we hope that this paper serves as a wake-up call for it.

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CRediT authorship contribution statement

Cati Torres: Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing, Writing – original draft. **Alicia Valero:** Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Antonio Valero:** Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **José Manuel Naredo:** Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing, Writing – original draft.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2025.108817>.

Data availability

Data will be available on request.

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