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A prediction of the exergy loss of the world's mineral reserves in the 21st century☆

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ABSTRACT

This paper makes an assessment of the exergy loss of the main minerals produced in the world throughout the 21st century, namely coal, oil, natural gas, iron, aluminium and copper. The reason for using the exergy analysis as an assessment tool is because it takes into account the main physical features that make a natural resource valuable: concentration, composition and quantity. Furthermore, using the same unit of measurement (energy) means all minerals considered can be compared and added. The future depletion degree of mineral reserves has been predicted with the help of five different scenarios. The first scenario assumes that production of all commodities will follow the well-known Hubbert's bell-shaped curve. The other four models are based on the (Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios) for fossil fuel consumption and the Hubbert peak model for non-fuel minerals. The results of this study indicate that there might not be enough available resources to satisfy the predicted future mineral demand.

1. Introduction

The exergy analysis has been proved to be a good indicator for resource accounting (see for instance, [1–5]). If resources are measured through the second law of thermodynamics in terms of exergy, we can integrate in a single indicator all the characteristics that describe a mineral resource: quantity (tonnage), chemical composition and concentration (grade). Exergy is measured in universal units (energy units) and is an additive property within resource accounting. Hence, it can be used as a global natural capital indicator, allowing comparison not only between minerals, but also between other types of resources.

In this paper, we will use the exergoecology approach proposed by Valero [6] to predict the exergy loss of world's mineral reserves in the 21st century. In this approach, the exergy assessment of natural resources is calculated according to the physical cost required to obtain them again from the materials contained in the reference environment. This reference environment is assumed to be a hypothetical Earth that has reached the maximum level of deterioration (see for instance [7] for details). Once the reference environment is established, the exergy of a non-fuel mineral resource is calculated as the sum of the chemical and concentration components. The latter values correspond to minimum exergies but, in fact, if we were to restore the depleted resources with current technology, much more exergy than the minimum dictated by nature would be required. This is why the exergoecological approach includes in the results the irreversibilities associated with current technology through exergy replacement costs explained below.

Throughout the 20th century, oil, natural gas and coal have been the most extracted fuels worldwide. On the other hand, iron, aluminium and copper dominate the world's non-fossil fuel extraction, representing more than 90% of the total exergy degradation in the 20th century and this tendency will probably continue in the current century. This is why in this paper we will focus on the latter six substances. Nevertheless, we should not forget the new age of high-tech metals such as In, Ge, Ta, etc. included in nanotechnology and microelectronics, which will become key minerals for industry. Furthermore, the extraction of other types of fuels such as tar sands, oil shales, natural bitumen or heavy crude oil might be economically competitive in this new century.

2. Methodology

The equations and detailed methodology used for calculating exergies (B) and exergy costs (B^*) are described in previous papers by the authors [7–9].

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The chemical specific exergy of any substance and in particular of minerals can be calculated using the following well-known expression [10]:

$$b_{ch} = \sum \nu_k b^0_{ch_{el,k}} + \Delta G_{mineral} \quad (1)$$

where $b_{ch_{el,k}}$ is the standard chemical exergy of the elements that compose the mineral and can be easily found in tables, ν_k is the number of moles of element k in the mineral and ΔG is the Gibbs free energy of the mineral.

The concentration exergy of a mineral is calculated by means of Eq. (2), which accounts for the minimum amount of energy – exergy – involved in concentrating a substance from an ideal mixture of two components [11]:

$$b_c = -\overline{R}T_0\left[\ln(x_i) + \frac{(1-x_i)}{x_i}\ln(1-x_i)\right] \quad (2)$$

where b_c is the concentration exergy, x_i is the molar concentration of substance i, $\overline{R}$ is the gas constant (8.3145 J/mol. K) and T_0 is the reference temperature (298.15 K). The difference between the concentration exergies obtained with the mineral concentration in a mine x_m and with the average concentration in the Earth's crust x_c is the minimum energy that nature had to spend to bring the minerals from the concentration in the reference state to the concentration in the mine.

Tsirlin and Titova [12] developed a more comprehensive expression of the reversible separation energy of an ideal mixture of components, taking into account linear kinetics. However, in the timeless limit, Tsirlin and Titova's model converges in Eq. (2).

For a more realistic calculation of the replacement costs of the mineral capital, we need to include in our calculation the so-called unit exergy replacement costs (k). The latter are multipliers of minimum exergies (b) and are defined as the relationship between the energy invested in the real process for refining (k_{ch}) or concentrating (k_c) the mineral, and the minimum exergy required if the same process were reversible. Hence, unit exergy replacement costs account for the “technological ignorance” which prevents us creating perfect (reversible) processes. Thus the, exergy replacement costs b_t^* are calculated with Eq. (3).

$$b_t^* = k_{ch} \cdot b_{ch} + k_c \cdot b_c \quad (3)$$

Table 1 shows the unit exergy replacement costs of the minerals considered in this paper.

Absolute exergies (B) and exergy costs (B^*) are obtained by multiplying specific exergies with tonnages.

2.1. The Hubbert peak analysis applied to exergy

On the other hand, using exergy, mineral extraction behaves similarly to the well-known Hubbert peak for fossil fuel resources [13]. The Hubbert peak model basically states that the production rate of oil in a particular region or the entire planet tends to follow a bell-shaped curve. Initially, production increases exponentially, until physical limits prevent this continuing. After reaching the peak, production curves become concave downward. Other authors have used Hubbert's curves to model production trends of minerals other than oil, such as Arndt and Roper [14] or Bardi and Pagani [15] for non-fuel minerals.

Table 1
Unit exergy costs of copper, iron and aluminium (updated from [26]).

Metal	k_c	k_{ch}
Cu	343.1	80.2
Fe	97.4	5.3
Al	2249.9	8.0

As demonstrated in the Australian case [16], the Hubbert peak represented with exergy over time instead of mass over time allows other important factors, such as concentration, to be included in the assessment. This is fundamental for solid minerals, since whereas oil quality keeps nearly constant with extraction, other non-fuel minerals' concentration decreases as the mine is being exploited. Moreover, if the Hubbert model is applied to the exergy replacement costs explained before, the technological factor of extracting and refining the mineral is also taken into account.

The model of the curve to be adjusted is given by Eq. (4):

$$f(t) = \frac{R}{b_0\sqrt{\pi}} e^{-\frac{(t-t_0)}{b_0}} \quad (4)$$

where parameters b_0 and t_0 are the unknowns and R the economic proven reserves of the commodity. The integral of $f(t)$ represents the total economic proven reserves.

In this paper, the yearly exergy replacement cost loss of the commodity calculated with Eq. (3) is represented vs. time. With a least squares procedure, the points are adjusted to the curve given by Eq. (4). Since the accounting unit is exergy, the analysis can be performed on single or aggregated resources. Furthermore, all studied substances can be represented in a single diagram.

This type of representation allows us to visualize and monitor the exergy evolution of mineral resources of the Earth and estimate when each resource will reach the maximum level of degradation, taking into account the geological proven reserves. Hence, the study based on the Hubbert peak analysis performed in this way can be assumed to be basically geologically driven. Obviously non-geologically-driven factors, such as reduced demand due to better substitutes, high oil prices preventing cost-effective mineral extraction, global economic crises, etc. can influence production rates. As a result, the quality of the fits may be affected but the peaks obtained will only change slightly [17].

2.2. The exergy of fossil fuels

Finally, the exergy of fuels was calculated with the procedure developed by Lozano and Valero [18] and assuming a single type of coal, oil and natural gas with the average properties estimated by Valero and Arauzo [19]. The average exergy of oil was assumed to be: 45,664 kJ/kg; of coal 22,692 kJ/kg coal and of natural gas: 39,394 kJ/kg. As opposed to the other types of minerals, fuels were only assessed in terms of exergy content and not exergy cost. Note that it is practically impossible to replace the fuels that have been burnt. That is not the case for non-fuel minerals; once used, their internal chemical exergy is not lost. Usually what happens is that minerals become dispersed in landfills, losing thereby the “natural exergy” bonus that nature gives us for free by providing minerals concentrated in mines and not dispersed in the Earth's crust [7]. Furthermore, the exergy of non-fuel minerals is insignificant when compared to that of fossil fuels. Hence, a “fair” comparison among the exergy loss of fossil fuels and non-fuel minerals is made using “exergy” for the former and “exergy replacement costs” for the latter.

3. Demand-driven scenarios

There are a great variety of demand-driven scenarios published about national and world energy consumptions. Two of the latest world scenarios are the ones carried out by the World Energy Council [20] and the International Energy Agency [21]. The WEC (World Energy Council) report, more focused on political actions, takes into account four scenarios, based on economic, population