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Evolution of the decrease in mineral exergy throughout the 20th century. The case of copper in the US

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Abstract

A mineral deposit is a natural resource whose exergy can be calculated from a defined reference environment (RE). This RE can be compared to a thermodynamically dead planet, where all materials have reacted, dispersed and mixed. Like any substance, a mine is characterized by its quantity, chemical composition and concentration (ore grade). The *mine's exergy* measures the minimum (reversible) energy to extract and concentrate the materials from the RE to the conditions in the mine. And the *mine's exergy replacement cost* accounts for the actual exergy required to accomplish this, with available technologies. The exergy assessment of the natural resource wealth of the Earth defined from a RE is named as exergoecology. The aim of this paper is to prove the usefulness of these two indicators for assessing the degradation of mineral deposits over history. As an example, the exergy decrease of US copper mines due to copper extraction throughout the 20th century has been determined. The results indicate that the exergy decrease was 65.4 Mtoe, while the exergy replacement cost 889.9 Mtoe. During the past century, the US extracted the equivalent of 2.5 and 1.2 times of its current national exergy reserves and base reserve of copper, respectively.

Keywords: Natural resources; Minerals; Chemical exergy; Concentration exergy; Exergy of a mine; Exergy replacement cost of a mine; Copper production; Exergy degradation

1. Introduction

The great economic growth experienced throughout the 20th century by many countries was mainly supported by the increasing extraction of natural resources, favored by technological innovation.

As the analysis of Meadows et al. [1,2] shows, the current exponential growth cannot longer be supported as naturally occurring substances become depleted. Some authors such as Barnett and Morse [3] or Scott and Pearse [4] appealed to the role of technological progress in improving the efficiency of extractive processes and redefining available resources. They stated that there is no evidence for the hypothesis that depletion of natural resources will lead to reduction of economic growth. On the contrary, Costanza and Daly [5], Ayres and Nair [6] or Cleveland and Ruth [7] believe that technology will not overcome resource scarcity and environmental degradation, since human capital ultimately is derived from and sustained by energy, materials and ecological services. Additionally, the argument that resource scarcity will be offset by resource substitution may be valid in the short term, but will fail in the long term when there is equal resource scarcity of all the substitutable materials [8].

The answer to whether there will be the imminent collapse forecasted by Meadows et al. or that there will be enough resources for the foreseeable future is still open. And it will probably remain open until more information about resource scarcity is provided. The true intertemporal scarcity of environmental goods must be analyzed and appropriate indicators for the scarcity of these goods must be found [9].

Measuring scarcity by means of monetary costs is not very effective, as discussed next. Even though non-renewable resources are becoming more and more scarce, prices have not followed the same trend. According to Hotelling [10], prices should raise with scarcity, since low-cost resources normally would be used first and quantities of extraction

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normally would decrease over time. On the contrary, historical statistics show that costs of extraction and prices have mostly decreased over time [11]. This apparent contradiction is due to technological innovation but also to the lack of information about scarcity. Reynolds [12] states that true scarcity is only revealed through prices towards the end of exhaustion. Until now, natural capital has been treated as a free good, but nowadays it is becoming the limiting factor in development [5].

Another way of measuring scarcity and natural resources depletion is by means of the second law of thermodynamics. Other authors have already studied and showed up the connection between economic scarcity and the entropy law [13,14].

The consumption of natural resources implies destruction of organized systems and pollution dispersion, which is in fact the generation of entropy or exergy destruction. This is why the exergy analysis can describe perfectly the degradation of natural capital. Exergy also quantifies the physical features that make a resource valuable: a particular composition which differentiates it from the surrounding environment, and a distribution which places it in a specific concentration [15,16]. Unlike standard economic valuations, the exergy analysis gives objective information since it is not subject to monetary policy, or currency speculation. Furthermore, all natural resources can be assessed in terms of exergy and can be added as a single entity. This is not the case if the evaluation is made in terms of mass: we cannot add tonnes of oil to tonnes of sillimanite, for instance.

Exergoecology is the name given by Valero [17] to the exergy assessment of the natural resource wealth of the Earth defined from a reference environment (RE). This RE can be associated to a thermodynamically dead planet, where all materials have reacted, dispersed and mixed. Provided that natural resources are being depleted by anthropogenic reasons, exergoecology can be used for quantifying the physical cost of replacing natural resources from the degraded state of the RE to the state found in nature. Exergoecology accounts for the thermodynamic distance between the dead planet and the mine.

Note that the "cumulative exergy consumption analysis" proposed by Szargut [18] accounts for the thermodynamic distance between the mine and a given final product. His thermo-ecological cost approach accounts for "the cumulative exergy consumption of non-renewable exergy connected with the fabrication of a particular product including the additional exergy consumption needed for the compensation of environmental losses caused by the disposal of harmful substances to the environment". For the case of copper, Szargut's analysis would account for the exergy input of all industrial processes involved in the production of pure copper from the mine (see Fig. 1). The exergoecology approach closes the cycle of Fig. 1, because it is concerned about the exergy needed to return the copper from the depleted state of the RE to the conditions of the mine where it was found. The exergy distance between the RE and the mine increases with the mine's quality. This means that as the mineral deposits become exhausted, the exergy difference between the RE and the mine becomes lower. In the limit, when all natural resources have been extracted and dispersed, this distance is equal to zero or, what is the same, the planet has lost all its natural exergy.

The authors of this paper do not intend that the word "exergoecology" should be preferred to "thermo-ecology". The aim is to stress with that word the main objective of our study, namely, the planetary exergy variation due to the anthropogenic presence. This analysis is not included in the concept of cumulative exergy consumption, but in the general theory of exergy cost proposed by Valero et al. [19]. However, the methodology we use for calculating the chemical exergy of any natural resource is entirely due to the work of Prof. Szargut.

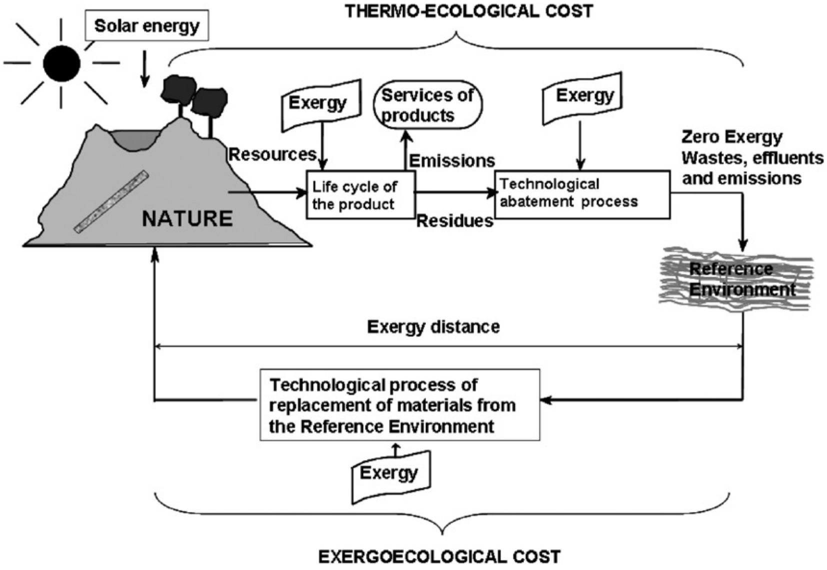

Fig. 1. Conceptual diagram of the terms exergoecology and thermo-ecology.