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A review of the use of exergy to evaluate the sustainability of fossil fuels and non-fuel mineral depletion

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ABSTRACT

This paper reviews methods that measure mineral resource depletion based on cumulative exergy consumption approaches. It focuses on the exergy replacement cost (ERC), which measures the amount of exergy society would have to consume in order to re-concentrate an extracted and processed mineral to the point that it can be once more exploited by future generations. The ERC, which was originally only suitable for non-fuel minerals, was adapted and extended in 2016, by changing the focus of the ERC from the chemical composition of the resource to its function, to include fossil fuel depletion. This paper discusses the impact of these new developments and identifies conceptual and methodological weaknesses that need to be addressed for the ERC to find widespread use in exergy analysis and in order to assess the sustainability of mineral policy from the grave to the cradle.

1. Introduction

Exergy is a useful universal unit of measure, which allows a practitioner to quantitatively state the physical cost of producing a product or a process. This is because it is an indicator which states the quality of energy, and not just its quantity. It can therefore be used to differentiate between one joule of heat at high temperature and one joule at a lower temperature. An exergy measurement is one way to gauge energy's real physical value, which allows for a more accurate evaluation of efficiency, and by extension the three pillars of sustainability. This is because of its contributions to process efficiencies and its use as a holistic approach to sustainable development [1,2]. In the sense that by identifying intense energy demands and circumventing or reducing them society can cut back on resource waste [3].

That said, exergy is not a typical choice for any form of quantitative analysis, even in the industrial sector, where it can be used to determine the efficiency of a process (such as the Rankine Cycle) or a component within a process (such as a boiler). Even those that work daily with efficiencies fill more comfortable when working with and talking in terms of energy, even though both energy and exergy make use of the same units (J, toe, etc). The lack of exergy adoption, as a measure of efficiency is even more acute when it comes to evaluating mineral policies and practices, from a physical perspective. This is true even at the theoretical level, which is how exergy will enter the general lexicon and practices of environmental scientists, geologists, engineers, or politicians who wish to quantitatively measure fuel and non-fuel mineral depletion.

As of 2016, there exists no review as to the use of exergy and its application to mineral resource sustainability, even though the tools to do so, at least for non-fuel minerals, have existed since 2000 [4]. The tool to measure non-fuel minerals, from an exergy perspective, was coined the exergy replacement cost, ERC for short [5]. It is a life cycle exergy assessment (LCEA) that goes from the grave to the cradle and has its roots in the cumulative exergy consumption approach developed by Szargut and Morris [6].

A means to calculate fossil fuel sustainability using exergy, was developed by Whiting et al. [7]. Their paper, by changing the focus of the method from a resource's chemical composition to its function, linked the conventional LCEA (cradle to grave) to the ERC (grave to cradle), via the use of biofuels (Fig. 1).

The aims of this present paper are: (1) to review the use of exergy, as a means to ascertain mineral resource sustainability and (2) to identify shortcomings in the cumulative exergy analysis and the ERC, when used in this context, (3) discuss the newest developments to the theory and where they fall short, which should encourage others to address them in future research. In theory, the ERC can be applied to any process or product to assess its sustainability, but this is a hunch that has yet to be tested – in part we believe due to the lack of a scientifically conducted review, hence the added value of our paper.

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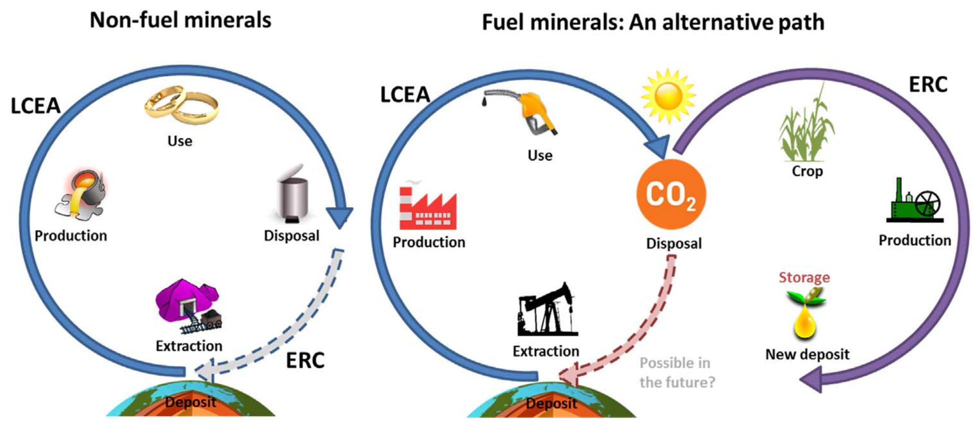

Fig. 1. Exergy cost flows in the cradle-to-grave and grave-to-cradle pathways.
Source: Authors.

2. Fundamental concepts: exergy and exergy analysis

2.1. Exergy explained

The concept of exergy can be demonstrated by the fact that one joule of heat at 30 °C is not the same as one joule of heat at 1000 °C and that one joule of heat at 1000 °C is not the same as one joule of work, even if they all measure one joule. Furthermore, one joule of work is more valuable than one joule of heat at 1000 °C, precisely because one joule of heat at 1000 °C can be used to produce a maximum amount of work of approximately 0.77 J.[1] One joule of heat at 30 °C is even less valuable because it produces a maximum amount of work of approximately 0.05 J. Therefore, not all energy forms are the same, because they do not produce the same maximum amount of work. Work has the highest conversion efficiency of all energy forms, which makes it the most valuable form of energy.

The exergy of an energy flow is the maximum amount of work that it can deliver (produce). Exergy can be used to quantitatively compare any energy form and work and heat relative to each other. In other words, it may be used to state energy's real value [8].

In any energy conversion process, energy is always conserved at the expense of exergy, which is always destroyed, unless the process is 100% reversible. The fact that something is irreversible means that energy quality has, or will deteriorate, because exergy has been and will always be consumed, in the same proportion as entropy is created. Exergy states exactly what is consumed in a system – natural or manmade – when energy or materials are transformed either for humanity's activities or natural processes.

Exergy has thermal, mechanical and chemical components, determined by temperature, pressure and chemical potential gradients. The quantity of exergy that may be extracted from a given process will depend on the surrounding environment. For example, to take temperature, the exergy contained within one joule of heat at 30 °C, in a process occurring at an ambient temperature of 15 °C, will be 0.05 J. But, if that same process occurred in an environment at 30 °C, then the exergy contained within the same joule will be zero because the temperature heat employed in the process and that of the ambient temperature is identical.

The need to select a suitable reference environment is often seen as a complex and cumbersome task, with the results seemingly difficult to interpret and understand [9]. However, the ability to measure exergy relies on a defined set of fixed substances within a system, in terms of both quality and quantity. Indeed, within exergy analysis, if one wishes to evaluate the maximum work extractable from a system, it is necessary to provide a reference state for the correct working of the method [10–12].

[1] The Carnot efficiency was estimated assuming an environmental temperature of 15°C

2.2. Exergy analysis

An exergy analysis defines the maximum performance of a system and specifies its irreversibilities [13]. This type of analysis is capable of pinpointing the exact location in a process where energy degradation has occurred, stating the sources of deviations from a system's ideal state [9]. An exergy analysis can be used to evaluate, analyse and optimise a given system [14]. Broadly speaking, an exergy analysis connects Physics and Economics through the Second Law of Thermodynamics. According to Torres et al. [15]:

Exergy is often used as a cost carrier because it is a sensitive magnitude to the changes of quality and quality of the energy processed and as a consequence more appropriate than energy in the measurement of efficiency.

Exergy analysis and its benefits, over a more conventional energy analysis, are most readily recognised in industrial processes. To use the Rankine Cycle as an example, an exergy analysis can correctly identify those irreversibilities that reduce a given process' ability to perform useful work. In this respect, the major losses, some 69%, can be linked to the boiler (due to combustion and heat transfers). An energy analysis, meanwhile, states that the majority of energy loss occurs when heat is rejected by the condenser. However, due to the low quality of this heat, an exergy practitioner does not consider this loss to have a significant impact on the process – in fact if one could theoretically remove the condenser, it would only contribute to a 3% improvement [16]. Therefore, a properly undertaken exergy analysis can lead to considerable technological and operational advances, whilst supporting sustainable development [17].

Away from industrial systems, an exergy analysis can describe perfectly the degradation of natural capital given that the consumption of natural resources implies destruction of organised systems and pollution dispersion, which is in fact a generation of entropy or exergy destruction [18]. The destruction of exergy can be represented through a concept called the specific exergy cost. The exergy cost of anything can be calculated as the quantity of exergy necessary to obtain it, as shown in Eq. (1).

$$\kappa = \frac{exergyinput}{exergyofproductoutputorusefulexergy}, \quad \text{whereexergy(in)} > \text{product exergy(out)} \tag{1}$$

To correctly evaluate exergy costs within a system, a clearly defined energy and material inventory is necessary, as are well stated boundaries, operations, processes, final products, sub-products and wastes. The value of exergy cost, k, correlates to efficiency, meaning that it can