Ecological Indicators 60 (2016) 603–610

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Material flow analysis for Europe: An exergoecological approach

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ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 31 May 2015
Accepted 4 August 2015

Keywords:
Material flow analysis
Sankey diagram
Exergy replacement cost
Mineral balance
Mineral trade

ABSTRACT

Material flow analysis is a key tool to quantify and monitor the use of natural resources. A very visual way to undertake such analyses representing the mineral trade is through Sankey diagrams, in which the mineral resources that are extracted, imported, exported, recycled and consumed within the given boundaries are represented with the arrows proportional to their respective quantities. Yet Sankey diagrams alone are not sensitive to the quality of the resources as they only reflect tonnage. This issue can lead to misleading conclusions and thereby not effective resource policies. A way to overcome this deficiency is representing the flows in exergy replacement cost (ERC) terms instead of tonnage. Exergy replacement cost is a concept derived from the second law of thermodynamics and assesses the exergy cost required to return with available technologies a given mineral to its initial conditions of composition and concentration in the mines where it was found, once it has been dispersed after use. Using this methodology, minerals are physically valued in terms of their respective scarcities and the effort (in exergy cost terms) required to produce them. Accordingly, in this paper the so-called exergoecology method is used to evaluate mineral trade and foreign mineral dependency in the EU-28 for 1995 to 2012. Using the year 2011 as a case study, it can be seen using this novel approach that 45.8% of the total input of minerals are imported resulting in lower values of self-sufficiency than if a traditional MFA were applied (0.45 for minerals and 0.41 for fossil fuels, in contrast to 0.79 and 0.52 obtained respectively when using tonnes). Analyzing 10 of the 20 minerals deemed critical by the European Commission, of the total internal production, 0.88% corresponded to critical minerals when data were expressed in tonnes and 3.19% when expressed in exergy replacement costs, highlighting their relevance respect to other minerals. This external dependency leaves Europe in a delicate situation regarding fossil fuels and non-fuel minerals supply highlighting the importance of recycling especially scarce minerals and searching for alternative sources.

1. Introduction

The 20th century has been characterized by a drastic increase in global material extraction. According to Krausmann et al. (2009), in 2005 the total material extraction was 8 times higher than in 1900, the strongest increase corresponding to construction minerals and to ore minerals. Although these data correspond to a global scale, the same trend can be extrapolated to smaller scales and economies. Despite having a rich endowment of mineral deposits, and producing 1.2% of the world level needs of iron or 1.4% of aluminium (BGS, 2011), European Union (EU) as a whole is dependent on extra-European sources for many substances. Giljum and Hubacek (2001) were the first authors to evaluate global foreign trade in the EU-15 for the period 1989–1999 through an input–output analysis, highlighting the external dependency and trade deficit of the EU economy. Later, Schütz et al. (2004) complemented these data comparing trade between 1976 and 2000. Additionally, they noted that between 41% and 63% of the physical imports came from developing countries, shifting the environmental pressure associated to mineral extraction and production to other regions.

While having a general overview of the trade situation is important, it is also basic to have studies that analyze the impact of materials separately. Even though Europe is self-sufficient regarding construction materials and industrial minerals, it heavily relies on metal imports, especially "high-tech" metals such as cobalt, platinum, rare earths and titanium. Concerning fossil fuels, the dependency and supply risk of the Member States have already been thoroughly analyzed by the European Commission (2013), stating that in the 2006–2010 period, 54% of the energy consumed within the European Union came from imports, a ratio substantially higher than the earlier decade (45% in 1999). Moreover 17

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http://dx.doi.org/10.1016/j.ecolind.2015.08.005
1470-160X/

countries belonging to the EU were considered vulnerable from an energy dependence point of view.

Following these studies, strategies at European level regarding raw materials supply and sustainable growth are being carried out. In that sense, to reach a resource-efficient Europe is one of the main objectives of the Europe 2020 Strategy (European Commission, 2011). Such is the criticality of this issue that in November 2008 the European Commission promoted the Raw Materials Initiative to establish a list of actions that the member states should implement (European Commission, 2008).

One tool that can help in shedding some light on the resource-efficiency of Europe, is the quantification of the use of natural resources. This evaluation is usually undertaken using material flow analysis, commonly used both at local and global scale (Schandl and Eisenmenger, 2006; Steinberg et al., 2010; Oras and Grüner, 2010; Eurostat, 2013). Particularly, the analysis of material flows is carried out through aggregated indicators that take into account minerals as a whole, sometimes differentiating at most industrial minerals, construction minerals and fossil fuels (Weisz et al., 2006; Bruckner et al., 2012; Kovanda et al., 2012; Kovanda and Weinzettel, 2013). Nevertheless it is becoming increasingly important to have knowledge of the impact and supply risk of all the materials using different methodologies (Mudd, 2007; Glaister and Mudd, 2010; Achzet and Helbig, 2013; Mudd, 2014; Valero et al., 2014). As a whole, this information could help providing valuable input for decision making processes aiming at improving the sustainability in the use of raw materials (Giljum et al., 2008; Tiess, 2010; Tiess and Kriz, 2011; Marinescu et al., 2013).

To overcome this issue, this paper undertakes an analysis of the mineral trade in Europe (EU-28) from 1995 to 2012. This material trade analysis is going to be firstly done accounting for the tonnes of each mineral that are produced, imported, exported and recycled, and representing those data through a conventional Sankey diagram. Subsequently, this same analysis will be undertaken using a thermodynamic approach, particularly using the so-called exergy replacement costs (ERC). This will allow us to compare results using both methodologies and analyze the existing differences regarding reliability and representativeness.

2. Methodology and data sources

Data for fossil fuels, including natural gas, oil and different types of coal, and a total of 40 non-fuel minerals have been taken into account in this study.

Information regarding domestic production, imports and exports from the period 1995 to 2012 has been obtained from the British Geological Survey European Mineral Statistics (BGS, 2014), completed with data from United States Geological Survey yearbooks of mineral statistics (USGS, 1995–2013). As individual data for recycling rates of each of the member states of the European Union are not available, average recycling rates for several metallic minerals have been used (UNEP, 2011).

In order to assess the mineral depletion more comprehensively, and to complement data in mass terms, the exergoecology method is applied (Valero, 1998). Exergoecology has been developed thus far for analyzing inorganic substances and can be divided into two distinct branches: Physical Hydronomics and Physical Geonomics. The former investigates water resources through the exergy assessment of ecological costs, i.e. those regarding the alteration of the physical and biological aspects of water bodies due to human activities (Valero et al., 2009). Jorgensen and Svirezhev (2004) and Jorgensen (2006) have also applied similar concepts to ecosystems, introducing the term Eco-exergy as a measure of how far an ecosystem is from thermodynamic equilibrium. Regarding Physical Geonomics, applying the exergoecology method we can evaluate the loss of natural resources through an exergy based indicator. As is well known, exergy is a property that is based on the second law of thermodynamics and that can be used to measure the quality of a system with respect to a given reference. While exergy has been widely used in the fields of process optimization, it can also be used to evaluate environmental impact assessment and resource accounting studies (Chen et al., 2014; Dai et al., 2014).

The exergoecology methodology consists on calculating the exergy that would be needed to replace a mineral deposit starting from an environment where all the minerals are dispersed to the initial conditions of composition and concentration found in the mine where it was originally extracted. To perform these calculations we need a model of average dispersed crust, *Thanatia*. This "planet" represents a possible state of the Earth where all fossil fuels have been consumed and where all minerals have been dispersed (Valero et al., 2011a, 2011b). This model includes a list of minerals with their respective concentration in the crust which delimits the lowest ore grades of the minerals. Therefore the exergy replacement costs of a mineral represent the exergy required to restore the minerals from Thanatia into the conditions found in Nature with the current available technology. ERCs are linked to the type of mineral analyzed, a deposit's average ore grade and the energy intensity of the mining and beneficiation process. Intrinsically, since quality is being taken into account in the calculations, scarcer and difficult to extract minerals (in terms of energy expended) carry more weight in the accounting process as the exergy needed to recover a mineral that is dispersed increases exponentially with scarcity. Accordingly for instance, limestone, a material that can be easily extracted and that is very abundant in the crust, has an exergy replacement cost of 2.6 GJ/tonne (Valero and Valero, 2014). If we look at scarcer minerals, such as gold or mercury, these values are 583,668 and 28,298 GJ/tonne respectively (Table 1). These numbers can provide hints of which minerals would be the most complicated to replace thereby also giving information about their quality. This is the reason why carrying out the analysis using only tonnage can result in biased information since it seems logical that one tonne of limestone should not have the same weight in the calculations as one tonne of gold.

The non-fuel substances that are included in this study are presented in Table 1, as well as their corresponding ERC. These data were obtained using the methodology described in Valero and Valero (2010).

In the case of fossil fuels, since once they are consumed and burned they cannot be replaced, it makes no sense to use the concept of exergy replacement costs. Alternatively, chemical exergy values are used, which can be approximated to their high heating values (HHV). The complete methodology is fully developed in Valero and Valero (2012).

3. Physical trade of minerals in the EU-28

European domestic production from 1995 to 2012 is depicted in Fig. 1 for non-fuel minerals (left) and for fossil fuels (right). Limestone was the predominant mineral extracted, accounting for an average of 85.3% of the yearly total production, followed by gypsum (8.7%) and salt (4.4%). The rest of the production corresponded to other minerals, mainly iron, aluminium and zinc.

Over the last years there has been a change in the tendency of domestic non-fuel mineral production. From 1995 to 2007 there was an increase in production reaching a maximum of 657 million tonnes extracted. Afterwards, this pattern changed towards a clear and drastic decrease. This can be attributed to a combination of resource management improvement and resource efficiency policies but also to the economic crisis which has been affecting the member states. Between 2007 and 2011 the domestic