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EXERGY ASSESSMENT OF MINERAL EXTRACTION, TRADE AND DEPLETION

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2016

Exergy assessment of mineral extraction, trade and depletion

By Guiomar Calvo Sevillano

PhD Dissertation

Supervisors:

Dr. Antonio Valero Capilla
Dr. Alicia Valero Delgado

Zaragoza, 2015.

Dr. Antonio Valero Capilla, catedrático del Área de Máquinas y Motores Térmicos de la Universidad de Zaragoza y director del Instituto Universitario de Investigación Mixto CIRCE-Universidad de Zaragoza,

Y

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CERTIFICAN

Que la presente memoria de Tesis Doctoral titulada:

"Exergy assessment of mineral extraction, trade and depletion "

Ha sido realizada por Dña. Guiomar Calvo Sevillano bajo nuestra dirección en el Instituto Universitario de Investigación Mixto CIRCE dentro del programa de Doctorado de Energías Renovables y Eficiencia Energética, y

AUTORIZAN su presentación como compendio de publicaciones.

Zaragoza, a 4 de noviembre de 2015

Fdo.: Dr. D.
Antonio Valero Capilla

Fdo.: Dr. Dña.
Alicia Valero Delgado

The current PhD dissertation “**Exergy assessment of mineral extraction, trade and depletion**”, submitted by Guiomar Calvo Sevillano and supervised by Antonio Valero Capilla and Alicia Valero Delgado, is presented as a compendium of the following papers:

1. Valero, A., Carpintero, Ó, Valero, A. Calvo, G. (2014). **Hoy to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study**. *Ecological Indicators*, 46, 548-559.

2. Valero, A., Valero, A., Calvo, G. (2015). **Using thermodynamics to improve the resource efficiency indicator GDP/DMC**. *Resources, Conservation and Recycling*, 94, 110-117.

3. Calvo, G., Valero, A., Valero, A., Carpintero, Ó. (2015). **An exergoecological analysis of the mineral economy in Spain.** *Energy*, 88, 2-8.

4. Calvo, G., Valero, A. and Valero, A. (2016). **Material flow analysis for Europe. An exergoecological approach**. *Ecological indicators*, 60, 603-610.

In addition to the items listed above, there are two other papers that are part of this thesis, one being reviewed by a journal and the other one under preparation.

ABSTRACT

Natural resources, especially minerals, are present in all products and are a vital component of society. Mineral consumption is experiencing an exponential increase and hence future availability is now playing a major role in resources efficiency policies. For this reason it is fundamental to have the best possible tools, objective and rigorous, that can help to properly account for this loss of resources. Studies cannot only be centered in analyzing current consumption patterns and reserves as it is happening now, but they need to take into account the gradual loss of future availability of resources due to mineral dispersion and the criticality of each of the materials.

By means of the Second Law of Thermodynamics, through property exergy and with a so-called Physical Geonomics approach, mineral extraction and dispersion can be assessed. Exergy, traditionally used to assess energy resources, can be also used to account for non-energy minerals. The advantage of this approach over other conventional ones is that it takes into account not only the quantity but also the quality of the given resource. Moreover, it is totally independent of monetary variations, thereby providing more accurate and objective information. Additionally, using this approach, one can easily cross over from the physical to the economic level, linking Thermodynamics with Economics, something that has been largely sought by the school of Ecological Economics.

As the basis of Physical Geonomics model was already established in previous studies, the first task of this PhD Dissertation has consisted on improving the available data. For this endeavor, an analysis on real data on energy consumption from different mining industries was performed to obtain new and more accurate data on energy consumption as a function of ore grade. Additionally, using the available information of fossil fuel and electricity consumption over the years, several energy intensity factors have been calculated. The general trend observed is that average ore grade slowly diminishes over time while energy consumption and production increases. Moreover, new data of exergy replacement costs for several mineral substances, meaning the exergy required restoring a resource from a complete dispersed state where no deposits exist to the physical and chemical conditions found in Nature with the available technology, has been calculated and has been added to the initial model.

The second task of this PhD Dissertation has been to propose a new indicator (GDP/DMD) that can be used at global level and that can evaluate natural resource efficiency. This new indicator takes into account not only the quantities of materials that are consumed within a region but also the quality of those materials, being able to put the focus on scarcer and critical substances. With GDP/DMD we can have a better and more accurate assessment of mineral depletion and it can be used to enhance more effective actions in the policy making process.

The third task has been to include Physical Geonomics into the Ecological Economics approach, which can be extremely helpful to evaluate natural resource efficiency use. One aspect that can be calculated using exergy replacement costs are the mineral market prices and the monetary loss associated to mineral extraction and depletion. Starting from the current mineral market prices, a new mineral price has been estimated considering that scarcity and not only economic factors are being taken into account. This allows seeing the distance between situations in which resources are treated as ordinary goods and situations in which they are treated as physical assets that need to be replaced.

Last, this new approach has been applied to several case studies. Spain, the European Union (EU-28) and Colombia have been chosen as examples of regions where mineral extraction and trade is substantial. Different factors, such as mineral depletion, foreign dependency, trade deficit and monetary loss associated to mineral depletion, have been calculated for each case. As demonstrated by all the case studies, carrying out a conventional material flow analysis to study mineral depletion is not enough, as material flow analysis and conventional indicators are usually related to monetary valuation and usually put together substances that are very different from each other, comparing “apples with oranges”. To complement this model and to obtain more realistic and accurate values, an exergy approach is needed, as using exergy replacement costs instead of tonnage as a yardstick we can place focus on the quality of the minerals and have a better overall picture of mineral depletion.

RESUMEN

Los recursos naturales, especialmente los minerales, están presentes en la práctica totalidad de los productos y son un componente vital para la sociedad. El consumo de materiales ha experimentado un crecimiento exponencial, que se ha acelerado especialmente en las últimas décadas, por lo que la futura disponibilidad de recursos está empezando a jugar un papel fundamental en las políticas relativas a la eficiencia en el uso de recursos. Por este motivo, es imprescindible contar con herramientas que sean lo más objetivas y rigurosas posible, que puedan ayudar a contabilizar de forma adecuada la pérdida de capital mineral relacionada con el consumo. Los estudios no deben centrarse solamente en analizar los patrones de consumo actuales y las reservas disponibles, tal como se hace hoy en día, también es necesario tener en cuenta la pérdida gradual de recursos en el futuro debido a la dispersión de los minerales y a su criticidad.

Mediante la Segunda Ley de la Termodinámica, a través de una propiedad llamada exergía y mediante la Geonomía Física, la extracción mineral y su dispersión pueden ser evaluadas. La exergía se ha usado tradicionalmente para evaluar recursos energéticos pero también puede emplearse en el caso de minerales no energéticos. La ventaja fundamental de este enfoque sobre otros métodos convencionales es que tiene en cuenta no solo la cantidad sino también la calidad de un recursos dado. Al mismo tiempo es una propiedad totalmente independiente de factores y variaciones monetarias, siendo así un indicador objetivo y preciso. Mediante este enfoque es sencillo pasar de un análisis económico a uno físico, uniendo la economía con la termodinámica, siendo este uno de los objetivos de la escuela de la Economía Ecológica.

Dado que la base de la Geonomía Física ya fue establecida en estudios previos, la primera tarea de esta tesis doctoral ha consistido en mejorar los datos disponibles. Para ello, se ha llevado a cabo un análisis de datos reales de consumo energético para obtener nuevos y más precisos valores sobre consumo de energía en función de la concentración de los minerales en la mina. Del mismo modo, empleando datos de consumo de electricidad y combustible diesel a lo largo de los años, se han obtenido distintos factores de uso energético. La tendencia general que muestran los datos es que cuanto más disminuye la ley del mineral en la mina, la cantidad de energía consumida aumenta. Partiendo de estos mismos datos, se han calculado nuevos costes exergéticos de reposición, es decir, la exergía necesaria para restaurar un recurso desde un estado completamente disperso hasta las condiciones físicas y químicas que se encuentran en la naturaleza empleando la tecnología disponible, para distintas sustancias.

El segundo objetivo ha sido proponer un nuevo indicador que pueda ser empleado a nivel global para evaluar la eficiencia en el uso de recursos naturales. Este nuevo indicador (GDP/DMD) tiene en cuenta no solo las cantidades de materiales que se consumen en una determinada región sino también la calidad de esos mismos materiales, siendo así capaz de hacer énfasis en aquellas más críticos y escasos. Con el indicador GDP/DMD se puede llevar a cabo un análisis mejor y más preciso de la dispersión mineral pudiéndose así emplear para promover

acciones más efectivas y concretas en las políticas enfocadas al estudio del consumo de recursos.

El tercer objetivo ha sido incluir la Geonomía Física dentro de la rama de estudio llamada Economía Ecológica, función que puede ser extremadamente útil para evaluar el uso de recursos. Un aspecto que puede ser calculado empleando los costes exergéticos de reposición son los precios del mercado de los minerales y la pérdida monetaria asociada a la extracción mineral y consecuente dispersión. Partiendo de los precios actuales de los minerales en el mercado, un nuevo valor puede ser estimado teniendo en cuenta su escasez y no solo factores económicos. Esto permite ver la distancia entre una situación donde los recursos son tratados exclusivamente como una mera mercancía y una situación en la que se tratan como activos físicos que deben ser reemplazados.

Finalmente, este enfoque ha sido aplicado a distintos casos de estudio. España, la Unión Europea (EU-28) y Colombia han sido elegidos como ejemplos de regiones donde la extracción y comercio de minerales tienen mucha importancia. Distintos factores, tales como el agotamiento de los recursos, la dependencia del exterior, el déficit comercial y la pérdida monetaria asociada a la dispersión de los minerales han sido calculados para cada uno de estos casos. Tal y como se ha podido demostrar en estos los estudios, llevar a cabo un análisis convencional de flujo de materiales no es suficiente a la hora de estudiar el agotamiento de los recursos minerales, ya que los análisis convencionales suelen estar relacionados con factores económicos y comparan sustancias que son muy distintas unas de otras, sumando así “peras con manzanas”. Para complementar este modelo y para obtener datos más realistas y precisos, se ha empleado la exergía, usando los costes exergéticos de reposición en vez de las toneladas como criterio básico, ya que así se puede hacer más énfasis en la calidad de los minerales y tener así una mejor aproximación de la situación general.

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A todos ellos, muchas gracias.

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1. INTRODUCTION

This PhD Dissertation was conducted at the Research Centre for Energy Resources and Consumption (CIRCE) and has been funded by the Spanish Ministry of Economy and Competitiveness (Project ENE2010-19834 and Project ENE2014-59933-R). It is framed within the PhD program in Renewable Energies and Energy Efficiency coordinated by CIRCE and Zaragoza University.

The aim of this section is to provide an overview of global mineral resources and management, along with criticality of raw materials, mineral depletion and sustainable development. As this PhD Dissertation is focused on the thermodynamic assessment of mineral capital, a review of the Physical Geonomics theory will also be performed to set the bases of the methodology which will be further used in the development of this research.

1.1. HISTORIC USE OF MINERALS

Extraction and of use of minerals has its origin at the beginning of humankind. Initially, mineral resources were obtained by surface collection, selecting those materials suitable for the construction of cutting tools, such as quartzite and chert, and for cosmetics and decorations. Thereafter, with the emergence of complex societies, mining started, focused on consumption and also on trading. Soon, the mineral processing changed substantially with the origin of metallurgical techniques of native metals and chemical methods to extract metallic minerals. The first metal to be smelted was copper, being a soft metal, it was eventually discovered that, when combined with tin, the result was a much harder metal: bronze. Gold and silver were also used as ornaments and for its economic value. Short after, iron was discovered, being iron sill the major hard material in use in modern civilization.

Additionally, gold started to be used, along with other precious metals, in commerce, being the oldest gold coin that is preserved more than 2,700 years old, found in Efesos (Asia Minor, current-day Turkey) and originated in the area of Lydia around 600BC (Schaps, 2006). This coin is actually made of electrum, a naturally occurring alloy of gold and silver, as the material used came from an electrum mine, which is quite rare as gold and silver usually appear separated.

Romans were the first to develop large scale mining methods, such as hydraulic mining, using large amounts of water to a variety of purposes, such as move sediment and excavate soft deposits. That is the case of *Las Médulas* deposit in Spain (Martín Escorza, 2006), considered the largest opencast goldmine of the Roman Empire (Figure 1). After a period of stagnation in the Middle Ages, where only iron was the most relevant material, during the Renaissance mining underwent over dramatic changes, as the industry and needs changed until reaching the importance it has today for providing the society.

Figure 1. Las Médulas (León, Spain).

1.2. CONSUMPTION OF RAW MATERIALS

Consumption of natural stock is a key element in current society, being economically, socially and culturally dependent, especially on minerals. Minerals have become an ever-present and vital component of our society and products that are used every day have mineral components that come from mining. There are virtually no products that contain no minerals or where minerals have not been used in their production. Base metals such as copper and zinc have a key role in those countries that are undergoing quick increases in social welfare, as they are essential to buildings, infrastructure, energy systems, automobiles, computers and mobile phones.

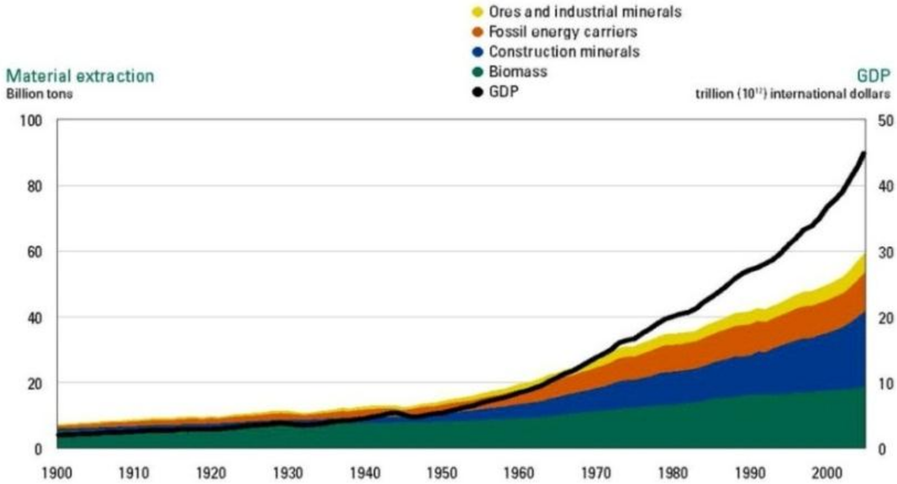

Figure 2 Global material extraction in billion tonnes from 1900 to 2005 (Krausmann et al., 2009).

On a worldwide scale there has been an exponential increasing trend of resource consumption in the last century. Some studies show that the global total material extraction increased over the 1900-2005 period by a factor of eight (Figure 2), the strongest increase corresponding to construction minerals and ores and industrial minerals, which grew by a factor of 34 and 27 respectively (Krausmann et al., 2009; UNEP, 2011a).

Figure 3 shows a bar diagram with the annual world production of mineral and energy resources for the year 1998 (Kippenberger, 2001). For comparative purposes, a bar diagram for the year 2014 has also been created (Figure 4) using several statistical services (British Petroleum, 2015; USGS, 2015a). Metallic minerals, represented in green, are mainly in the upper half of the diagram, while industrial and construction minerals, represented in light orange, are in the lower part. In the base of the pyramid we can find the most extracted minerals, which are mainly industrial minerals and fossil fuels, used to cover the basic needs of the society such as transport, heating and housing.

Between 1998 and 2014 there are not many differences in the production pattern but the main changes observed are related to the quantities extracted. The average extraction increase between these two years for the substances represented in Figure 3 and Figure 4 was 39.3%. In both years the base of the pyramid is formed by extraction of fossil fuels, as it could be expected, and metallic substances and critical metals are mainly located in the upper half. On the other hand, the production of metallic minerals, such as zinc, titanium, manganese and chromium became more relevant in 2014, with chromium and titanium increasing approximately 86% and 81% respectively. Regarding critical metals, such as germanium and indium, they experienced a 66 and 72% increase respectively. In the case of gallium there is no extraction data available for 1998 but in 2014 the amount extracted globally was 440 tonnes.

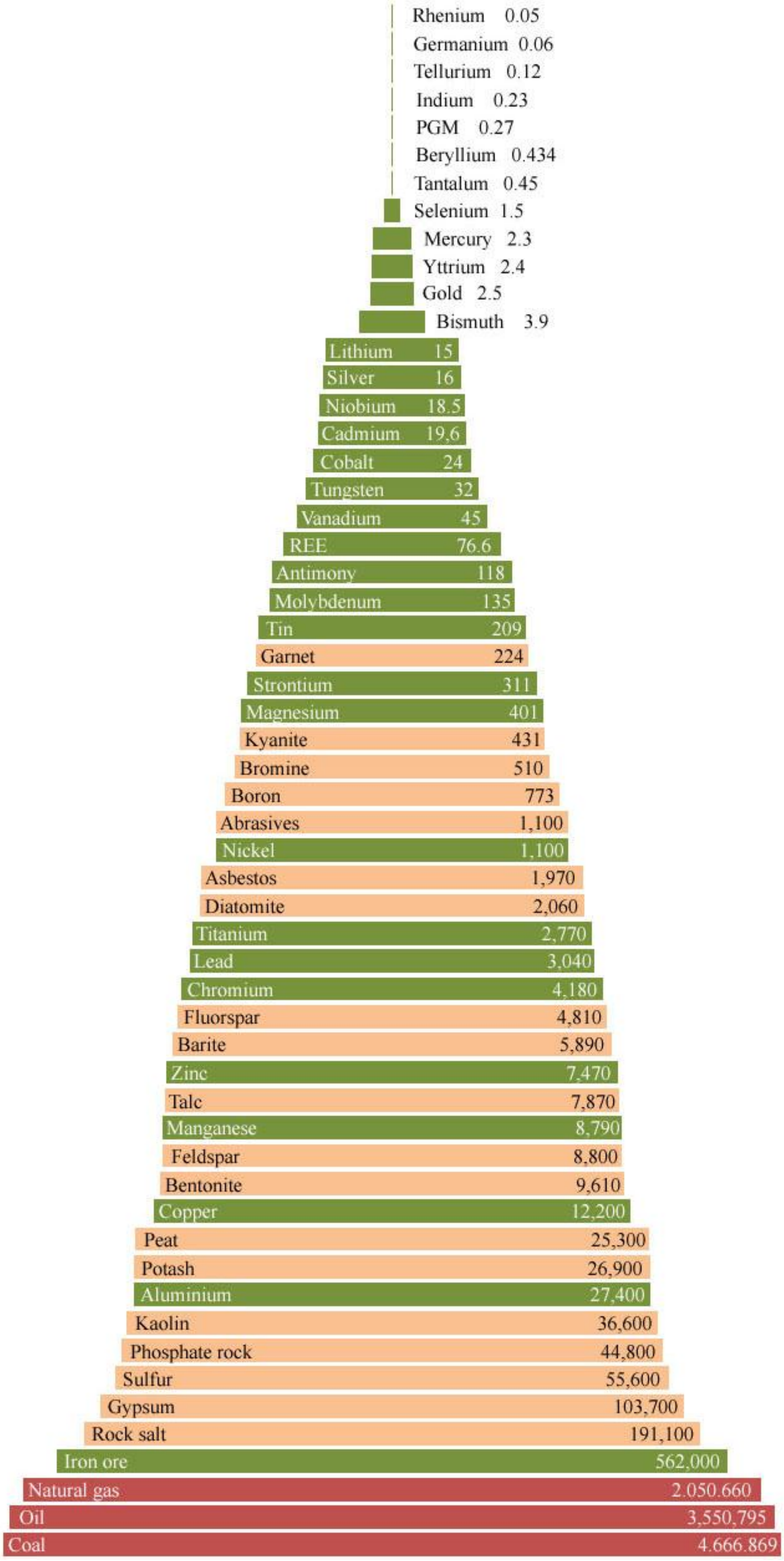

Figure 3. World primary production of mineral and energy resources in 1998 (modified from Kippenberger, 2001); production is in thousand metric tonnes.

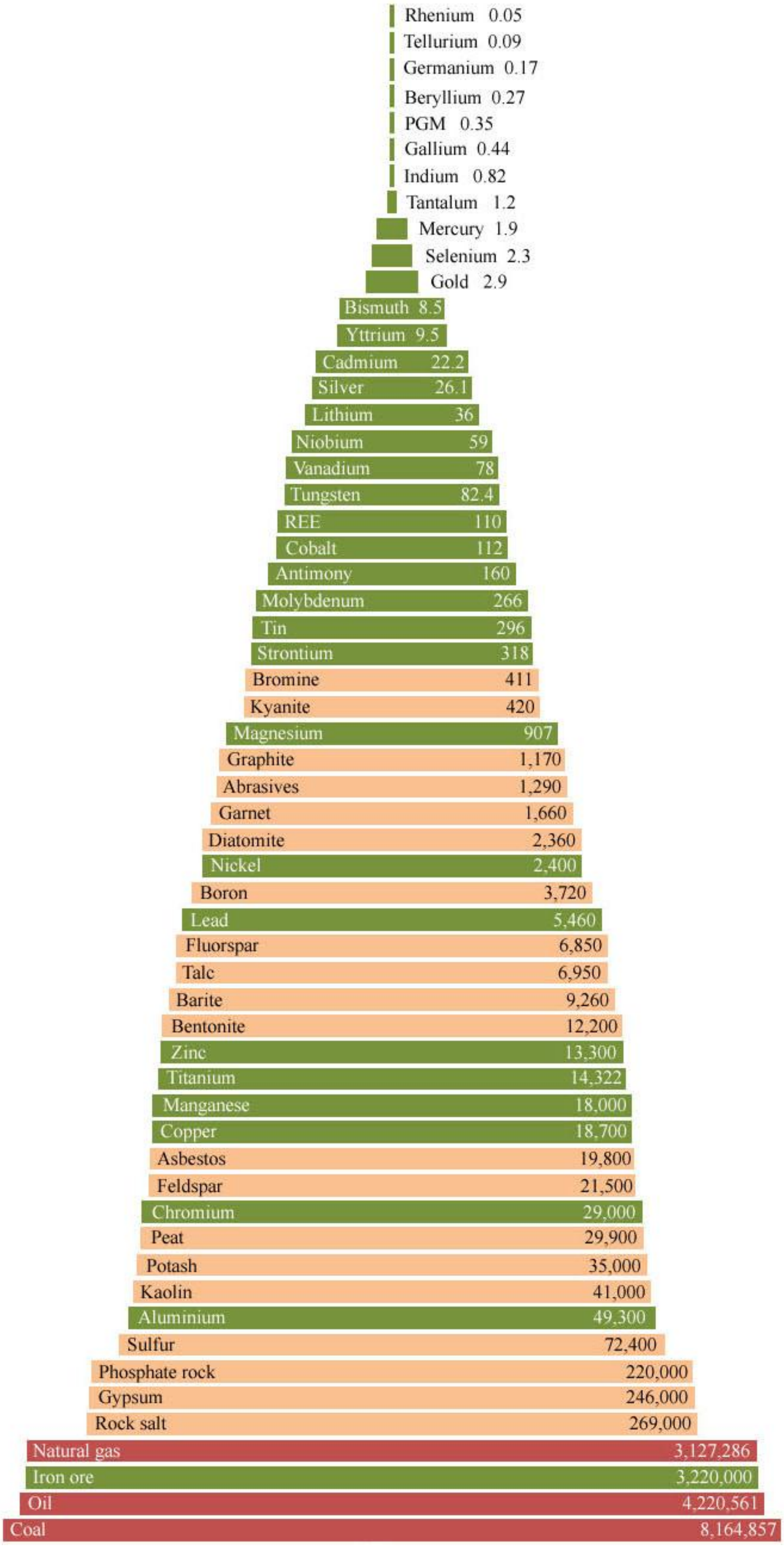

Figure 4. World primary production of mineral and energy resources in 2014 (British Petroleum, 2015; USGS, 2015a); production is in thousand metric tonnes.

When comparing the world primary production for these two years for selected non-fuel mineral commodities (Table 1), the global increase soon becomes clear. The average increase of the substances presented in the table between 1998 and 2014 was 43.2%, with only two commodities whose production decreased during that period of time, kyanite and talc. For the rest of the substances, the ones with higher increases are asbestos, boron, phosphate rock and titanium. Noteworthy is the change in iron ore extraction, as in 2014 it even exceeded natural gas extraction, increasing between 1998 and 2014 by almost 83%. Observing the behaviour of non-fuel minerals separated by main groups, industrial minerals and metallic minerals, their average increases are 35 and 51% respectively. These results are in accordance with the importance and criticality that metallic mineral have in modern society.

Table 1. Comparative analysis between the world production for selected non-fuel commodities for the years 1998 and 2014 (British Petroleum, 2015; Kippenberger, 2001; USGS, 2015a).

Commodity	**1998 (thousand tonnes)**	**2014 (thousand tonnes)**	**Variation (%)**
Non-fuel minerals			
Aluminium	27,400	49,300	+44.4
Antimony	118	160	+26.3
Asbestos	1,970	19,800	+90.1
Barite	5,890	9,260	+36.4
Bentonite	9,610	12,200	+21.2
Boron	773	3,720	+79.2
Chromium	4,180	29,000	+85.6
Cobalt	24	112	+78.6
Copper	12,200	18,700	+34.8
Diatomite	2,060	2,360	+12.7
Feldspar	8,800	21,500	+59.1
Fluorspar	4,810	6,850	+29.8
Gold	2.5	2.9	+12.6
Graphite (natural)	648	1,170	+44.6
Gypsum	103,700	246,000	+57.8
Iron ore	562,000	3,220,000	+82.5
Kaolin	36,600	41,000	+10.7
Kyanite	431	420	-2.6
Lead	3,040	5,460	+44.3
Magnesium (metal)	401	907	+55.8
Manganese	8,790	18,000	+51.2
Molybdenum	135	266	+49.2
Nickel	1,100	2,400	+54.2
Peat	25,300	29,900	+15.4

Commodity	1998 (thousand tonnes)	2014 (thousand tonnes)	Variation (%)
Phosphate rock	44,800	220,000	+79.6
Potash	26,900	35,000	+23.1
Rock salt	191,100	269,000	+29.0
Silver	16	26	+38.7
Sulfur	55,600	72,400	+23.2
Talc	7,870	6,950	-13.2
Tin	209	296	+29.4
Titanium	2,770	14,322	+80.7
Tungsten	32	82	+61.2
Vanadium	45	78	+42.3
Zinc	7,470	13,300	+43.8
Fossil fuels			
Natural gas	2,051	3,127	+34.4
Oil	3,551	4,221	+15.9
Coal	4,667	8,165	+42.8

Fossil fuels follow the same trend as the other natural resources, being the average production increase between those two years of 31%, the largest increase corresponding to coal extraction, which almost doubled its production.

Analyzing the global mineral production is useful to have general trends on mineral extraction and consumption, and this same increasing tendency can be observed on a smaller scale (Figure 5). Over the past decades, Australian production of iron ore, silver, zinc and copper show strong near to exponential growth over time.

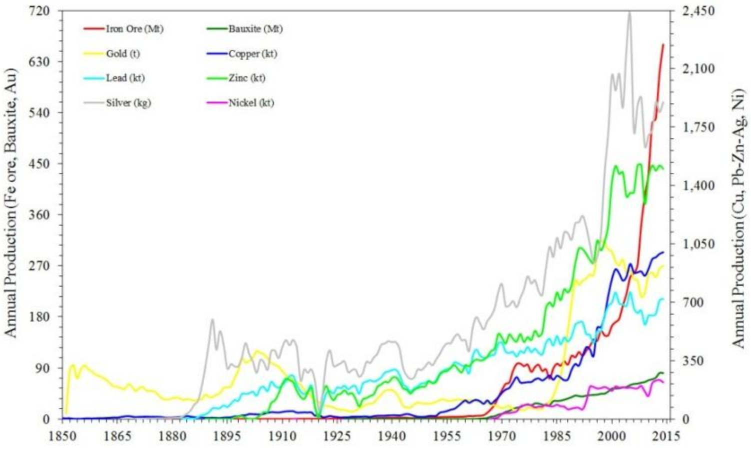

Figure 5. Australian production for selected metallic substances (modified from Mudd, 2010b).

This highly intensive use and extraction of mineral resources has led to many reports to better assess the impact that the human being is having on the planet. According to the Minerals Education Coalition, using data from the United States Geological Survey Mineral Commodity Summaries and the Energy information Administration, the average American will need in their lifetime 3.11 million pounds (approximately 1.4 million kilograms) of minerals, metals and fuels (Minerals Education Coalition, 2015). Additionally, every year 17,940 kg of new minerals must be provided for every person in the United States to make the goods they use every day, including more than 2,600 kg of coal, 22 barrels of petroleum and 2,500 cubic meters of natural gas. Among others, 30 kg of aluminium, used to make buildings, beverage containers, cars and airplanes, 5 kg of lead, used for batteries, for communication and TV screen, as well as 3 kg of zinc, used to make metals rust resistant, various metals and alloys, paint, rubber or skin creams. Regarding industrial and construction minerals, more than 1,500 kilograms between stone, sand, gravel, cement and clays must be provided to make bricks, buildings, roads, houses, bridges and paper (Minerals Education Coalition, 2015).

In Europe, meanwhile, the average amount of extraction of resources during year 2000 was around 13 tonnes per capita, or 36 kg per day (Friends of the Earth, 2009). When compared with North America, Oceania or Africa, being 68, 58, and 15 kg per person per day respectively, one can easily state that there is a great variation globally. When analyzing the consumption per capita, these numbers change drastically. In Europe, 43 kg are consumed per person per day, 88 in North America, 100 in Oceania and only 10 in Africa, meaning that an average European consumes as many as four times more resources than an average African. When observing European countries individually, differences in both material consumption per capita and material productivity can be observed, ranging from 3.8 tonnes of domestic material consumption per capita in Malta to over 50 in Ireland (European Environment Agency, 2012). With this consumption rate, we might be compromising the availability of natural resources for future generations; this is why it is critical to invest in research and exploration as well as in recycling and particularly in natural resources management and assessment techniques.

Based on the aforementioned data, it can be inferred that management and depletion of natural resources is a very important issue that humankind is facing nowadays and especially in the case of metallic and nonmetallic resources as they are normally considered to be nonrenewable. One way to predict future availability of non-renewable resources and measure the depletion degree is the ratio between known reserves and production (R/P ratio). Using long-term projection for selected minerals, the years to exhaustion using 1979 and 2000 production levels were predicted using reserve base.[1] and reserves.[2] information

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[1] Reserve base: that part of an identified resource that meets specific minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness and depth. (*Identified resource: resources whose location, grade, quality and quantity are known or estimated).*

[2] Reserve: that part of the reserve base which could be economically extracted or produced at the time of determination.

(Leontief et al., 1983; Sohn, 2006). Of the eight minerals studied, only copper, mercury and tin showed potential medium-term prospects for reserve exhaustion, being the years to exhaustion using 2000 production levels 35.61, 36.14 and 21.94 respectively. Accordingly, a similar study was carried out for energy projections of coal, natural gas and oil for a 30 year interval, stating that the projected global total fossil fuel consumption from 1970-200 was 3.3% while the observed annual growth was 2.3% over the same period (Sohn, 2007). Additionally, more recent studies have predicted the depletion times of scarce minerals and their relationship with sustainability (Harmsen et al., 2013; Henckens et al., 2014).

With this similar R/P approach, (Valero & Valero, 2010) with 2008 data obtained that humankind had approximately depleted 26% of its world non-fuel mineral reserves, being mercury, silver, gold, tin and arsenic the most depleted commodities. An important shortcoming of this approach is that production and reserves are considered static and hence, these predictions are at risk of soon being outdated due to new discoveries of mineral deposits, better assessment of reserves and changes in the consumption and growth rates.

Another way to better predict mineral behavior is through the so-called Hubbert peak theory, which has been extensively used to evaluate fossil fuel peaking production and depletion (Hubbert, 1956; 1962). Contrarily to the previous one, it is a dynamic model in terms of production and assumes that after fossil fuels reserves are discovered, production first increases exponentially but at some point a peak output is reached and then production begins to decline again exponentially, generating a bell-shaped curve when the production is represented as a function of time. Hubbert originally predicted that the petroleum peak worldwide would be reached in 2005 (Figure 6). However, this theory fails to consider resource growth, new deposit discoveries, and application of new technologies to deposits that were not economically viable before, commercial factors or geopolitics.

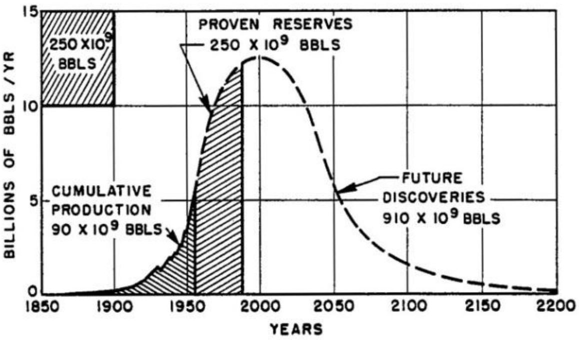

Figure 6. Hubbert's prediction of world petroleum production rates (Hubbert, 1956).

From the development of this methodology a large number of studies have been conducted, analyzing the global and local current and future patterns of oil consumption and depletion (Capellán-Pérez et al., 2014; Chapman, 2014; Chavez-Rodriguez et al., 2015; García-Olivares & Ballabrera-Poy, 2015; Maggio & Cacciola, 2012; Reynolds, 2014). Other studies have also focused on the status of coal production and forecast future production using historical production data and estimates of recoverable resources (Milici et al., 2013; Mohr & Evans, 2009; Patzek & Croft, 2010; Reaver & Khare, 2014).

In the case of non-fuel minerals, this issue has been addressed from several points of view but still there is a disagreement in the mineral depletion approach (Tilton, 2003). Studies regarding several base metals, including studies of declining ore grades in mines and mining associated environmental constraints have been carried out analyzing the historical production and furthermore trying to assess the future availability (UNEP., 2010; Mason et al., 2011; Mudd, 2007a, 2007c, 2009b, 2010a; Northey et al., 2014; Prior et al., 2012; Tilton & Lagos, 2007; Yaksic & Tilton, 2009). Using the shape of cumulative availability curves, meaning the amount of a mineral commodity that can be recovered profitably at various prices from different types of mineral deposits under the current conditions, can also provide helpful information about the potential shortages caused by depletion, although the information needed to construct these cumulative availability curves is not always available for all the commodities (Tilton, 2001, 2003; Yaksic & Tilton, 2009).

As the Hubbert model can only be applied where the concentration is not important, other methodologies were needed to take that factor into account (Valero, Valero, & Torres, 2008). Combining exergy analysis and Hubbert peak models, an exergy countdown was obtained, showing that coal could last for 120 years, oil for 52, natural gas for 70 and non-fuel minerals for 126 as an average, using the consumption rate of the year 2010 as a reference (Valero & Valero, 2014). In any case, all these studies assume that no more resources are discovered or are available in the future, so the results obtained must be considered only as an approximation of the depletion state of the reserves under “business as usual” scenarios.

In short, even if extraction is currently exponentially increasing, millions of years have been needed to form the mineral deposits, concentrating the different elements through a large number of geological processes, and it is clear that the extraction ratios are unbalanced. Additionally, mining is a very energy consuming process, without energy there are no minerals but without minerals there is no energy. According to the International Energy Agency (IEA), between 8 and 10% of the world total energy consumption is dedicated to the extraction of materials that the society demands, and that number does not take into account metallurgical processes, transport and other mining related activities (Antonio Valero, 2012). For this reason, analyzing the energy use and energy intensity in mines is crucial to have a better knowledge of the impact that the mining sector has.

1.3. ENERGY USE IN THE MINING INDUSTRY

Mining industry requires greats amounts of energy to extract and process resources, including a variety of concentration and refining processes, which normally depend on the mineral extracted, the ore grade, economic issues and mining conditions, among other factors.

Mines can be classified according to several criteria, depending on the basic mining technique, underground or open cut, or according to the process configuration of the mine. Open pit mining includes excavating rock, removing waste rock to a disposal area and the ore to a processing plant. Underground mines are more energy consuming as all the material has to be transported to the surface, ore and waste rock, and it also includes other activities such as drilling, blasting, mechanic ventilation, water drainage, etc. Afterwards the ore is concentrated and refined in the plant, after the crushing and grinding stages, which can include a number of metallurgical processes depending on the ore mined.

Due to intensive extraction and declining ore grades, mines now tend to be excavated deeper and deeper into the crust and more commercially worthless material needs to be removed to obtain the same amount of ore than before. Huge amounts of energy are required then to extract minerals. Additionally, the mining industry is very water dependent, i.e., to produce a tonne of gold, over 250 Ml of water are required (Norgate & Lovel, 2004).

Analyzing the energy intensity use in mining could lead to progress towards a better sustainable industry, therefore it seems fundamental to include this issue in the study. In Table 2 a series of average numbers of energy intensity can be found for selected mineral commodities.

Table 2. Energy requirements for the production of several mineral commodities (GJ/t) (Domínguez, 2014).

Substance	Mining and beneficiation	Smelting and refining
Aluminium (gibbsite)	10.5	23.9
Antimonium (stibnite)	1.4	12
Chromium (chromite)	0.01	36.3
Copper (chalcopyrite)	28.8	21.4
Gold	107751.8	-
Iron (hematite)	0.7	13.4
Lead (galena)	0,9	3.3
Manganese (pyrolusite)	0.2	57.4
Mercury (cinnabar)	157.0	252
Potassium (sylvite)	3.1	-
Silver (argentite)	1281.4	284.8
Tin (cassiterite)	15.2	11.4
Wolfram (scheelite)	213.0	381
Zinc (sphalerite)	1.5	40.4

Still, in literature a wide range of values for each commodity can be found as there are other factors that can affect the energy use in mines, such as changes in the ore grade, grain size, depth of the mine, material cohesion or technical constraints. Several studies are focusing on the energy requirements by processes, compiling real information and improving the calculation methodology using characterization factors (CF) to evaluate resource scarcity, tools that can be later applied in LCA (De Meester et al., 2006; Norgate, 2010; Norgate & Haque, 2010; Norgate & Jahanshahi, 2010b; Vieira et al., 2012). Additionally, the energy consumption related to by-product extraction is not always available as they are very dependent on the demand of the metal they are associated with.

Multiple studies have shown that energy consumption increases when ore grade decreases, as is the case of gold (Figure 7), but still there are very little studies that compile energy requirements for different commodities due to the lack of reliable information (Chapman & Roberts, 1983; Mudd, 2007b; Norgate et al., 2007; Talens & Villalba, 2013; Valero & Valero, 2014).

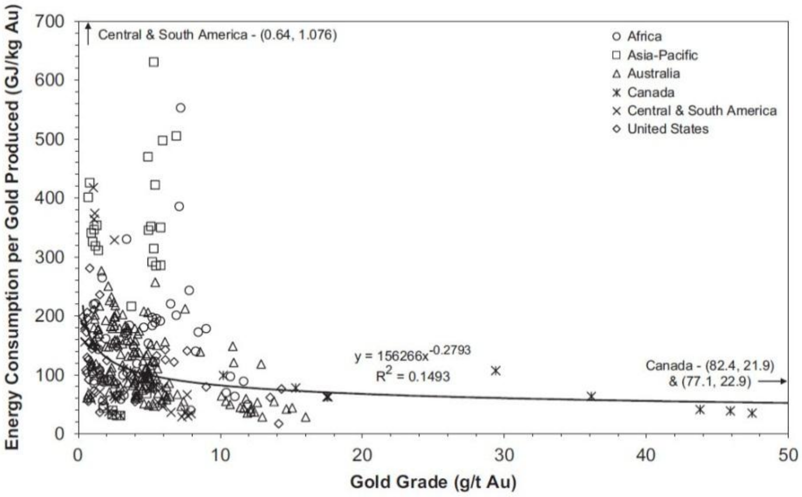

Figure 7. Energy consumption (GJ/kg Au) as a function of ore grade (g/t Au) (Mudd, 2007b).

In mining, an increase in energy efficiency does not necessarily imply an energy reduction, as one of the key variables is ore grade. The impact of technology changes was modeled for the case of copper, showing that high specific ore demands are typically linked to less energy intensive extraction technologies (Swart & Dewulf, 2013a). In the case of gold, it has been demonstrated that although progress in technology has been made, the energy requirements are increasing (Domínguez & Valero, 2013).

Analyzing the energy consumption per gold produced and per tonne of ore milled in Australia (Figure 8), the results showed an average of 123 GJ/kg Au and 0.31GJ/t ore. Some mines show a decline of energy consumption over time due to implementation of efficiency measures, however other mines have increased their consumption over time (Mudd, 2007c). Besides, unit consumption of water, consumption of cyanide and CO_2 emissions follows similar trends to those of energy, increasing when ore grade decreases. Similar studies have been carried out for other commodities, such as uranium, platinum group metals (PGM), copper, nickel, lead and zinc (Mudd, 2007a, 2010a, 2012, 2014; Yellishetty & Mudd, 2014).

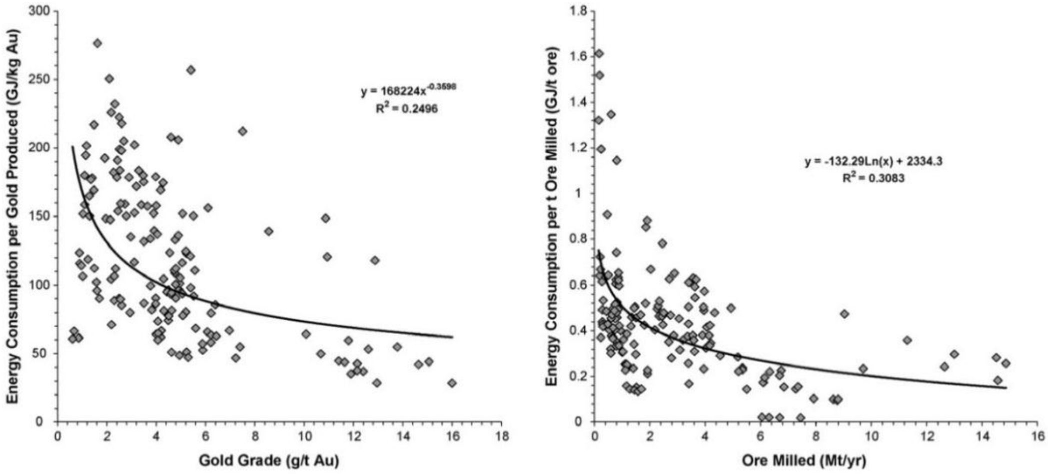

Figure 8. Energy consumption in gold mining (Mudd, 2007c).

Using energy consumption information, different sustainability issues can be addressed, such as the relationship with ore grade over the years, energy variations in electricity or fossil fuel use, environmental footprint of mining processes, etc. (Glaister & Mudd, 2010; Northey et al. , 2013). Further studies must be centered not only on the evaluation of mineral depletion over the years, but also take into account the criticality for the society of each separate mineral. Avoiding shortages and highlighting where to put the focus on recycling policies, especially in the case of metallic minerals that are used for new technologies, should be a critical issue.

1.4. CRITICALITY OF MINERALS

Gradually many regions and countries are focusing on raw material needs and raw material supply, moving towards a more sustainable and resource efficient society. Such is the criticality of this issue that in November 2008 the European Commission promoted the Raw Materials Initiative to establish the raw material strategy and a list of actions that the member states should implement (European Commission, 2008). Additionally, in June 2010 the European Commission published a report on critical raw materials for the European Union (European Commission, 2010) which identified 14 minerals as critical for the EU. This report was later updated (European Commission, 2014) expanding the list and including antimony, beryllium, borates, chromium, cobalt, coking coal, fluorspar, gallium, germanium, indium, magnesite, magnesium, natural graphite, niobium, PGM (platinum group metals), phosphate rock, both heavy and light REE (Rare Earth Elements), silicon metal and tungsten as critical raw materials (Figure 9).

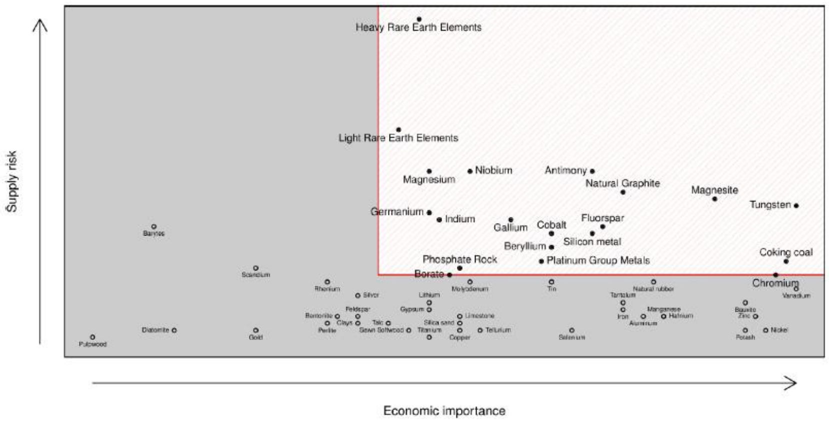

Figure 9. Critical raw materials for the European Union for 2013 according to supply risk and economic importance of each substance (European Commission, 2014).

Similarly, the Committee on Critical Mineral Impacts of the U.S. Economy also published an experts report on critical minerals to the U.S. to aid decision makers (Committee on Critical Mineral Impacts of the US Economy, 2008) that was subsequently updated by the U.S. Department of Energy in December 2011 (U.S. Department of Energy, 2011). A criticality matrix was developed, taking into account five factors that can limit the long-term availability in the case of non-fuel minerals: geology, technology, environmental and social issues, politics and economics. This matrix was applied to eleven minerals, listed here: copper, gallium, indium, lithium, manganese, niobium, platinum group elements, rare earths, tantalum, titanium and vanadium (Figure 10). After carrying out an analysis of the minerals and materials used in the United States taking into account availability and reliability of supply, the United States proved to be completely dependent on imports on five: indium, manganese, niobium, PGM and REE.

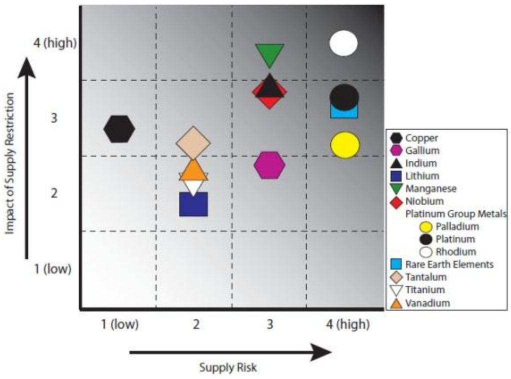

Figure 10. Criticality matrix for the 11 materials assessed by the Committee on Critical Mineral Impacts on the U.S. Economy (Committee on Critical Mineral Impacts of the US Economy, 2008) .

With similar concerns, the American Physical Society (APS) and the Materials Research Society (MRS) released a study in 2011 about the Energy-critical Elements (ECEs), chemical elements that have the capacity transforming the way of capturing, transmitting, storing or conserving energy, that are necessary to develop one or more new, energy-related technologies, i.e., electric cars, wind turbines and solar cells (Figure 11).

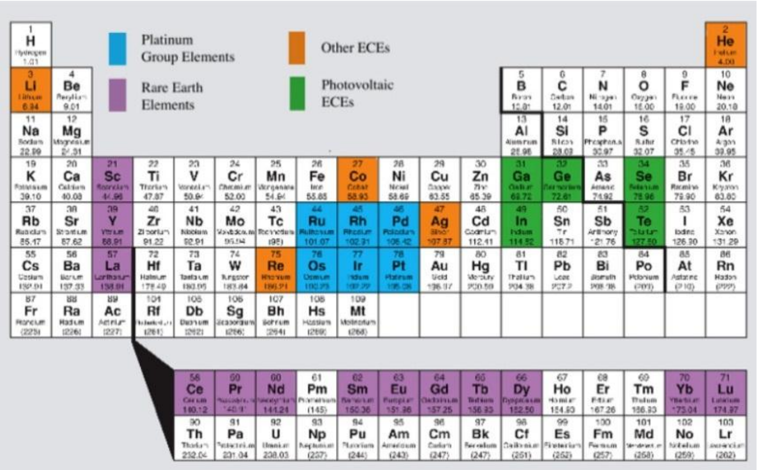

Figure 11. Energy-critical Elements (ECEs) highlighted on the periodic table (from American Physical Society & Materials Research Society 2011).

These ECEs include rare earths, but also more than a dozen other chemical elements such as gallium, germanium, indium, platinum, cobalt, silver or lithium (American Physical Society & Materials Research Society, 2011).

All these reports have in common that they have labeled as critical the same minerals (indium, manganese, niobium, PGM, REE…), materials that are used in mobile phones, fluorescent lights, hybrid cars and in the manufacture of renewable technologies such as wind turbines and solar panels. But criticality alone should not only take into account economic factors or supply risk, as there are other factors that come into play when talking about natural resources. This is the case of energy use, as stated before, which is a very important element in the mining industry, or the case of the increasing rates in natural resources consumption. It is thus necessary to find a way to use all these physical factors, along with material dispersion, to provide useful and accurate information at policy making stages. Indicators, as they are based on several factors, can be used as powerful tools to summarize in just one numeraire a series of important issues that can be additionally used for comparative purposes.

1.5. RESOURCE EFFICIENCY INDICATORS

One tool that can help in shedding some light on raw material use and depletion is the quantification of the use of natural resources, with emphasis on mineral use and dispersion. This evaluation is usually undertaken using material flow analysis (MFA), commonly used both at local and global scale (Adriaanse et al., 1997; Browne et al., 2011; Kovanda & Hak, 2011; Rosado et al., 2014; Sastre et al., 2015; Schandl & Eisenmenger, 2006; Steinberger et al., 2010). Additionally, it is even a standardized methodology that is applied in statistical offices of many countries (Eurostat, 2013; Oras & Grüner, 2010). 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 (Bruckner et al., 2012; Kovanda et al., 2012; Kovanda & Weinzettel, 2013; Weisz et al., 2006). Nevertheless it is becoming increasingly important to have knowledge of the impact and supply risk of all the materials using different methodologies and to be able to assess individually the supply risk and relevance of each separate mineral (Achzet & Helbig, 2013; Glaister & Mudd, 2010; Mudd, 2007c, 2014; Rosenau-Tornow et al., 2009). 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; Marinescu et al., 2013; Tiess, 2010).

A better management of mineral resources and improvements in resource efficiency is critical to secure future availability of natural resources. For such an endeavor, the impact of the human being on the environment must be reduced and the resources have to be consumed in a more intelligent fashion. Therefore, based on the available information, robust and easily understandable indicators can be developed in order to monitor or measure the progress towards sustainability.

In the same way that the use of gross domestic product (GDP) is widely spread to measure the income at national level, over the last decades plenty of indicators have been developed and suggested in regard to sustainable development. Some examples are the Ecological Footprint (EF), Human Development Index (HDI) or the Happy Planet Index. Other indicators based on energy, land and water use from micro to macro level were discussed by Giljum et al. (2011). Each of these indicators provides a different type of information, being complementary rather than competitive, and can help to better assess the impact of policies on natural resource use.

A series of indicators can be derived from economy-wide material flow accounts, providing information on essential characteristics of the socio-industrial metabolism. They can be grouped into input, output, consumption, balance, productivity and consistency indicators (Bringezu & Schütz, 2010). The most commonly used material consumption indicators are direct material input (DMI), domestic material consumption (DMC), total material requirement (TMR), total material consumption (TMC), net additions to stock (NAS) and physical trade balance (PTB) (Eurostat, 2001). DMI represents the input of materials for use in an economy, meaning all materials which are of economic value and which are available for use in production and consumption activities. DMC indicator measures the total amount of materials directly used by an economy and is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports. TMR includes both material used for further processing (DMI) and hidden flows, in other words, the materials that are not used further but that haven an environmental impact. TMC includes the use of all domestic and foreign primary materials for production and consumption. NAS measures the physical growth of the economy, meaning the quantity of new construction materials used in infrastructures and materials incorporated into new durable goods. PTB measures the physical trade surplus or deficit of an economy, calculated as imports minus exports.

Besides using DMC as a standalone indicator for resource efficiency, DMC can be easily combined with GDP to evaluate resource productivity. The European Commission (EC) recently developed the Roadmap to a Resource Efficient Europe (COM (2011) 571) (European Commission, 2011). This was carried out in response to unsustainable over-use of environmental resources and increased price volatility, and also in its recognition of the essential role played by both mineral and environmental resources in providing economic stability and growth. Environmental resources include rare earth metals, water, climate, fish, biomass, fertile soils, clean air and ecosystem services. The European Commission proposed to use precisely as the lead indicator “Resource Productivity”, GDP divided by DMC in euro/ton. Even if they recognize this indicator has some considerable drawbacks, such as that it is insensitive to changes in the environmental pressures and that the economic value, scarcity and the environmental impacts are only partially correlated to the weight of the resources. To compensate its limitations, this lead indicator is intended to be complemented with a dashboard of macro indicators and some specific indicators to measure progress towards the specific objectives and actions.

The main drawbacks is that these indicators are frequently linked to economic factors and it is important to find tools to measure decoupling of resource use from the economic growth and decoupling of environmental impact from resource use, still currently some efforts are being made in this regard. Van der Voet et al. (2005) proposed the environmentally weighted material consumption (EMC), an indicator that combines information on material flows with information on environmental impacts. Giegrich & Leibich (2008) proposed the environmental impact load (EVIL), which combines different impacts which affect environmental safeguard subjects. EVIL corresponds to the acceptable maximum of environmental impacts which guarantee the sustainable development of society. Since it is based on political conventions, the quantification can be subject to changes according to existing and developing knowledge and value judgments. Recently the Japanese government introduced indicators based on specific solid waste management and material flow analysis, which helped to increase significantly its recycling levels and reduce the amount of final disposal waste (Yabar et al., 2012). Additionally, having a systematized framework of indicators related to resource efficiency and use of natural resources can help their use and implementation at government or scientific level (Huysman et al., 2015).

Nevertheless, indicators that combine different methodologies need to be developed, being at the same time easily applicable at policy making levels and providing the maximum possible amount of information. Throughout history, ecological economists have tried to overcome this issue, developing accounting systems to integrate resource repletion in the economic realm and analyzing its effects in the economy. Thus, this evolution will be discussed next.

1.6. RESOURCE DEPLETION AND THE ECONOMY

Although the origin of the concerns of mineral depletion can be dated back to classical economics in the late 18th and early 19th centuries (Malthus, 1798; Mill, 1848; Ricardo, 1817), it was not until the beginning of the 20th century when a theory on natural resources economics was developed. Regarding non-renewable resources, Harold Hotelling's seminal contribution can be considered as the starting point of natural resources neoclassical economics (Hotelling, 1931). Hotelling proposed a rule for optimal extraction of an exhaustible resource ensuring profit maximization in a market under perfect competition conditions. In these circumstances, the price should depend on the marginal revenue and the evolution of the interest rate. The unrealistic character of assumptions behind this approach and the difficulty in operationalizing this proposal leave it basically as a theoretical suggestion.

During the last decades several studies have focused on the relationship between economic growth and scarcity of natural resources using different approaches and scenarios (Simpson et al., 2005). On one hand Barnett and Morse (1963) collected price and costs for minerals, among other substances, over time, stating that prices had fallen or remained constant, being non-dependent on physical scarcity. Therefore, concluding that resource scarcity was not threatening economic growth. On the other hand, the issue of resource depletion, among others, was explored by the Club of Rome (Meadows et al., 1972), analyzing the evolution of several variables throughout different scenarios, which was successively updated (Meadows et al., 1993; Meadows et al., 2004). The main conclusion was that the economy would collapse if no actions were undertaken and that, once the limit was attained, the human society would be forced to reduce its rate of resource use and emissions.

At the end of 1980's, the debate about depletion of natural resources strongly emerged at the macro level in relation to ecological flaws in the Systems of National Accounts (SNA) and the possibilities of an ecological adjust of macro magnitudes (El Serafy, 1989, 2013; United Nations, 2003). The SNA is an internationally agreed standard, intended to be used by all countries, that has a set of recommendations on how to collect measures of economic activity in accordance with strict conventions based on economic principles (European Commission, 2009). Using these recommendations allows economic data to be compiled and presented in a format that can be used for economic analysis, decision taking and policy making processes. As it is well known, the most widely accepted measure of a country's economic progress is gross domestic product (GDP) as it measures the value of the economy's aggregate output of final goods and services in a given period of time. The main problem is that the current GDP calculation process does not take into account the degradation of natural resources (Costanza et al., 2009; Daly, 1990; Lawn, 2006; Van der Bergh, 2010).

There is a debate whether the total capital stock should be kept constant in monetary terms (weak sustainability) or in physical terms (strong sustainability). The weak sustainability approach assumes that natural and manufactured capitals are substitutable and that there are not differences between the well-being they generate, the only fact that matters is the total value of the aggregate stock of capital (Neumayer, 2003, 2012). On the other side there is the strong sustainability approach, that demonstrates that natural capital cannot be viewed only as a stock of resources but as a rather complex system (Brand, 2009; De Groot et al., 2003; Noël & O'Connor, 1998).

Literature on natural resource accounting usually takes a weak sustainability approach and distinguishes between two general methods to account for the depletion of natural resources into SNA: the net price method and the user cost method. The net price method is based on the Hotelling rent theory, discussed previously, which states that the price of a depletable resource includes two components: the production cost and the resource rent or depletion cost. The Hotelling rent is then defined as the price of the resource minus the marginal costs of extraction. Given the assumptions of perfect competition, it implies to maximize the present value of expected future rents, which multiplied by the resource quantity extracted is considered the depreciation of the natural resource (asset) and should be deducted from the Net Domestic Product (Hartwick & Hageman, 1993; Repetto et al., 1989; Rubio, 2005).

Contrarily, Salah El Serafy showed that the depreciation method is problematic when applied to countries with abundant deposits of mineral resources. This result leads to another general method to adjust national accounts: the user's cost method (El Serafy, 1989). In this case, mineral deposits and other natural resources are considered as assets and, by their very nature, their selling does not create added value. This circumstance should be enough not to include the revenue obtained from the sale in GDP. However, given the sale generates a monetary stream, which can be consumed or, in part, invested in alternative uses, we can obtain a perpetual "true income" from this investment that it would be part of GDP and we can enjoy it after the resource is wasted up. The distinction between the "true income" and the total receipts (net of extraction cost) from the sale of mineral resource is a fundamental point in this scheme. It allows differentiating what part of total receipts should be considered as a "true income" and, on the contrary, what part should be treated as loss of "natural capital" and excluded from GDP. The difference between the true income and total receipts from resource sale is the so-called user's cost or factor depletion (El Serafy, 1989, 2013).

Nonetheless, both methods can be used to calculate incomes associated to extraction of exhaustible resources. There are, however, several shortcomings when applying these methods. For instance, net price method assumes perfect competition, which is almost never met. Also that resource rent, meaning the difference between total revenue generated from the extraction of natural resources and all costs incurred during the extraction, will rise at a rate equal to the discount rate of the future. On the other hand, in order to calculate the user's cost, El Serafy's method uses the net price as a starting point, with the aforementioned problems. It also assumes a constant discount rate chosen by the analyst, a constant rate of extraction until a resource is exhausted, and for that very reason, a constant level of receipts during the assumed lifetime of resources.

To avoid some of the problems related to monetary valuation and weak sustainability perspective, physical and monetary dimensions must be linked to more solid foundations. In this regard, ecological economics provides better prospects. Not in vain, right from the beginning this approach built bridges between economics and natural sciences devoted to study the characteristics and behavior of energy and materials. Nicholas Georgescu-Roegen (1906-1994), a mathematician, statistician and economist, can be considered the father of Ecological economics, which is defined as an interdisciplinary field that addresses the relationship between ecosystems and economic systems (Costanza, 1989). Although the issue had already been discussed earlier (Daly, 1968), one of the first efforts to bring ecologists and economist together occurred in 1982, in a Symposium in Sweden called "*Integrating Ecology and Economics*" (Jansson, 1984). During this meeting the large gap between both fields became clear and that a new approach was needed. The first book addressing this issue was "*Ecological economics: energy, environment and society*", by Martínez-Alier (1987). Following more meetings, the creation of a specific journal (Ecological economics) and a society (International Society for Ecological Economics, ISEE) this new field is now a reality.

Indeed, from this point onwards many contributions appeared that analyze the relationship between economics and other fields, such as Thermodynamics, particularly with regard to the physical aspects of the production process of goods and services and its analytical representation (Ayres et al., 2003; Ayres & Warr, 2009; Bamungärtner, 2004; Baumungärtner et al., 2006; Faber et al., 1987; Faber & Proops, 1996; Georgescu-Roegen, 1971, 1977; Naredo & Valero, 1999; Ruth, 1993).

1.7. THERMODYNAMIC ASSESSMENT OF MINERAL RESOURCES

The link between Ecological Economics and Thermodynamics was created in 1971, with the book "*The Entropy Law and the Economic Process*", written by Georgescu-Roegen (1971). In this book, the author stated that increasing rates of natural resource extraction will lead to entropic degradation of the Earth. Entropy is a thermodynamic property, measured in Joules per Kelvin, which has been widely used in the ecological economics field. Entropy, a rather abstract concept, can be used as a measure of disorder. It is a property that can be applied to micro and macroeconomic processes and be used to analyze the interactions between the economy and the environment. Still, entropy was used only as a qualitative measure through terms such as "low entropy" or "high entropy" rather than to conduct a thorough quantitative analysis that could be used to evaluate the yearly destruction of the natural capital of the Earth.

This issue could be overcome using Thermodynamics, specifically using exergy. This new property was developed in 1956 (Rant, 1956), and is defined as the minimum amount of work that may be theoretically performed by bringing a system into equilibrium with its surrounding environment by a series of reversible processes. Starting from exergy the concept of exergy cost or embodied exergy was introduced, which is defined as the sum of all resources required to build a product from its component parts expressed in exergy units. This is clearly a Thermodynamic concept but it shares many aspects with Economics, resulting a theory that connects both of them: Thermoeconomics, an energy based approach (Antonio Valero, 1998).

Therefore, to assess mineral resources exergy is a better option, as it is a property sensitive to quantity and also quality, it is additive and can be calculated in all flows interacting with any manufacturing process. It is a powerful tool widely used to improve the efficiency of processes and system optimization. While energy is never destroyed during a process, exergy is, so the exergy analysis can be used to account for the irreversibility in a process and to identify the interactions among system components and potential for improvement. For this reason, exergy analysis has been extensively applied in the design, evaluation, optimization and improvement of power plants (Kaushik et al., 2011; Keçebaş & Gökgedik, 2015; Regulagadda et al., 2010; Yamankaradeniz, 2016) but also in other fields as varied as economics, physics and biology (Bligh & Ismet, 2012; Ertesvåg & Mielnik, 2000; Li et al., 2013; Reistad, 1975; Taelman et al., 2014; Talens et al., 2007; Van der Vorst et al., 2009; Vargas-Parra et al., 2013).

As stated before, with exergy we can consider both quantity and quality of the resources in the analysis, while the conventional approach of natural resources evaluation, traditionally based on mass terms, fails to evaluate the latter. Therefore, exergy can be used to evaluate environmental impact assessment and resource accounting (Chen et al., 2014; Dai et al., 2014).

One exergy based approach focused on the amount of exergy required to produce a certain good is the thermo-ecological cost analysis. The thermo-ecological costs is based on the cumulative consumption of non-renewable exergy connected with the fabrication of a particular product, with the additional inclusion of the consumption resulting from the necessity of compensating the environmental loss (Szargut et al., 2002; Szargut, 2005). The thermo-ecological cost approach is based on the cumulate exergy consumption, which is the same concept as exergy cost analysis (Szargut & Morris, 1987; Valero et al., 1986). Additionally both concepts, cumulative exergy consumption and exergy cost, are updated versions of the former embodied energy (Hannon, 1973). The exergy cost is the amount of the resources measured in exergy terms required to build a product and is widely used in Thermoeconomics to optimize and improve industrial processes. Thermoeconomics integrates Thermodynamics and Economics by means of the Second Law, explaining the physical bases of the cost and uniting the cost with the physical processes in which the sacrifice of physical resources is located, causalised and quantified in terms of thermodynamic irreversibility (Valero, 1998).

The Exergoecology approach, meanwhile, derived from Thermoeconomics, can be used to assess natural resources using exergy. 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). Other authors (Jorgensen & Svirezhev, 2004; 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, that is to say how developed an ecosystem is. Regarding Physical Geonomics, applying the exergoecology method we can evaluate the loss of natural resources through exergy, a property that is based on the second law of Thermodynamics.

Conventional exergy analysis only account for the exergy consumed from the initial to the final state of a commodity or good, the so-called cradle-to-grave approach. Starting from all the raw materials needed from the earth to create the product or good, this type of analysis estimates the cumulate environmental impacts resulting from all stages in the product or good life cycle (atmospheric emissions, residues, wastes generated, etc.).

However, Physical Geonomics closes this cycle, carrying out an analysis from grave-to-cradle, from an environment where all the minerals are dispersed to the original conditions as they are found in Nature, including a new stage in the global analysis (Figure 12).

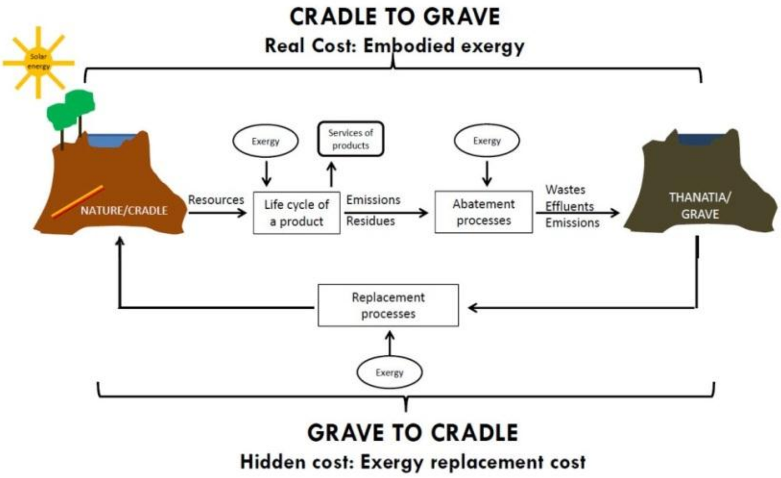

Figure 12. Diagram of the cradle-to-grave and grave-to-cradle approach (Valero & Valero, 2014).

Physical Geonomics (Valero, 1998) 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, a baseline coined *Thanatia* (Valero, Valero, & Gómez, 2011; Valero, Agudelo, & Valero, 2011). This "planet" represents a possible state of the Earth where all fossil fuels have been consumed and where all minerals have been dispersed, accordingly it also has specific atmospheric conditions. This model includes a list of minerals with their respective concentration in the crust (x_c) which delimits the lowest ore grades of the minerals and that is used as a boundary to carry out the calculations (Table 3).

Table 3. Selected values for the concentration in the crust in Thanatia (x_c) and the concentration in the mine (x_m) of selected substances (Valero & Valero, 2014).

Substance	x_c **[g/g]**	x_m **[g/g]**
Aluminium (gibbsite)	1.38E^{-03}	7.03E^{-01}
Cobalt (linnaeite)	5.15E^{-09}	1.90E^{-03}
Copper (chalcopyrite)	6.64E^{-05}	1.67E^{-02}
Gold	1.28E^{-09}	2.24E^{-06}
Iron ore (hematite)	9.66E^{-04}	7.30E^{-01}
Lead (galena)	6.67E^{-06}	2.37E^{-02}
Manganese (pyrolusite)	4.90E^{-05}	5.00E^{-01}
Mercury (cinnabar)	5.73E^{-08}	4.41E^{-03}
Molybdenum (molybdenite)	1.83E^{-06}	5.01E^{-04}
Silver (argentite)	1.24E^{-08}	4.27E^{-06}
Tin (cassiterite)	2.61E^{-06}	6.09E^{-03}
Wolfram (scheelite)	2.67E^{-06}	8.94E^{-03}
Zinc (sphalerite)	9.96E^{-05}	6.05E^{-02}

To perform this grave-to-cradle analysis, thermodynamic tools are used to calculate exergy and exergy costs, properties derived from the second law of Thermodynamics.

The total exergy of a mineral deposit can be calculated as the sum of chemical exergy (b_{ch}), concentration exergy (b_c) and comminution exergy (b_{com}). The chemical composition has a direct influence of the energy required to process the mineral. The chemical exergy (b_{ch}) is equivalent to the minimum theoretical work needed to obtain the resource at a specific composition from the reference environment and it can be calculated with the following expression (Equation 1):

$$b_{ch,i} = \Delta G_{f,i} + \sum r_{j,i}\, b_{ch,j} \qquad \text{(Eq. 1)}$$

Where $b_{ch,j}$ is the standard chemical exergy of the element j contained in substance i, $r_{j,i}$ is the number of moles of element j per mole of substance i, and $\Delta G_{f,i}$ is the Gibbs free energy of the substance i (Valero, 2008).

The concentration exergy (b_c) is the minimum theoretical work needed to provide minerals at a specific concentration with respect to the dispersed state, in this case Thanatia, and is given by the following equation (Equation 2):

$$b_{c,i} = -RT^0\left[lnx_i + \frac{(1-x_i)}{x_i}\ln(1-x_i)\right] \qquad \text{(Eq. 2)}$$

Where x_i is the concentration of substance i, R is the gas constant (8.314 J/molK) and T^0 is the reference temperature (298.15 K). This formula is only valid for ideal mixtures and when there is no chemical cohesion among the substances it is also valid for solid mixtures.

Comminution exergy (b_{com}) represents the minimum exergy required to bind solids from a given dispersed state to a more cohesive one. However, when compared with chemical or concentration exergy, comminution exergy is not significant and can be ignored in the calculations of the total exergy of a certain mineral (Valero & Valero, 2012). Hence, the total exergy is the sum of the aforementioned components, chemical composition and concentration exergy (Equation 3):

$$b_t = b_{ch} + b_c \qquad \text{(Eq. 3)}$$

The chemical exergy is obtained from the reference environment but the calculation of the concentration exergy implies the knowledge of the average ore grade in the mine (x_m), as well as the average concentration in the Earth's crust in Thanatia (x_c). The difference between $b_c(x_c)$ and $b_c(x_m)$ represents the minimum exergy required to form the mineral as found in the mineral deposits from the concentration in Thanatia (Equation 4).

$$\Delta b_c(x_c \rightarrow\ x_m) = b_c\ (x = x_c) - b_c(x = x_m) \qquad \text{(Eq. 4)}$$

Using only exergy to evaluate mineral depletion provides only a partial vision of the real situation as this approach considers all resource generation processes as reversible, providing then minimum values. If we were to concentrate the mineral resources with current available technology, much more energy would be required. For this reason, to include irreversibilities associated with current technology, exergy replacement costs are used. The exergy replacement costs (ERC) of a resource was first defined by Valero (1998) as the exergy required by a *given available technology* to return a resource from a dispersed state, Thanatia, to the physical and chemical conditions found in Nature. As it happens with exergy, exergy replacement costs (b_t^*) also has three contributions. The first contribution is the chemical costs, accounting for the chemical production process of the substance, and the second one the concentration cost, accounting for the concentration process. Theoretically, the third contribution, comminution cost, should also be taken into account but, as it happens with comminution exergy, it is negligible when compared to the chemical or concentration exergy so it can be excluded from the calculations. This way, the exergy replacement costs calculation remains as follows (Equation 5):

$$b_t^* = k_{ch} b_{ch} + k_c b_c = b_{ch}^* + b_c^* \qquad \text{(Eq. 5)}$$

The dimensionless variable k represents the unit exergy cost of a mineral and is defined as the ratio between the energy invested in the real obtaining process, for mining and concentrating the mineral from the ore (x_m) to the pre-smelting and refining grade conditions (x_r), and the minimum theoretical exergy required if the process was reversible (Equation 6).

$$k = \frac{E(x_m \rightarrow x_r)}{\Delta b_{x_m \rightarrow x_r}} \qquad \text{(Eq. 6)}$$

Therefore k is a measure of the irreversibility of man-made processes and amplifies minimum exergy by a factor of ten to several thousand times, depending on the commodity analyzed.

The chemical exergy cost of the resource *(b_{ch}^*)* is used when the chosen reference environment does not contain the substance under consideration. As Thanatia already contains most of the minerals found in the crust, the chemical exergy is not needed in the case of non-fuel minerals. Non-fuel minerals do not disappear when disposed of, therefore the only property that is lost in the process is concentration. In the case of fossil fuels, as they cannot be replaced or reproduced once they are burned, only its chemical exergy should be considered.

In these calculations we are assuming that the technology applied is the same between the ore grade in the mine and the pre-smelting grade and between Thanatia and the mine. Additionally, information on the energy required in the mining and concentration process is not always available, so it becomes necessary to analyze the average energy vs. ore grade trends and calculate and extrapolate to the ore grades corresponding to those in Thanatia *(x_c).*

Energy consumption data as a function of the ore grade are usually difficult to find and there are few studies that address this issue (Mudd, 2007b, 2010c; T. Norgate & Jahanshahi, 2010a). A general theoretical formula has been proposed to calculate the energy requirements of several metals (P. F. Chapman & Roberts, 1983), differentiating between the energy used in mining and the one used in concentrating. This approach assumes that the energy required in mining and concentration is inversely proportional to the ore grade. Still, as there is a lack of information regarding this issue, it is necessary to work with empirical and theoretical data.

The general formula to calculate energy consumption as a function of ore grade is presented in Equation 7. It follows an exponential curve, meaning that the energy required for mining grows exponentially when ore grade decreases.

$$E(x_m) = A \cdot {x_m}^{-0.5} \qquad \text{(Eq. 7)}$$

Where x_m is the metal concentration expressed as a mass percentage of the element under consideration and coefficient A is determined for each mineral, as the average ore grades (x_m) and the energy required for extracting and concentrating the mineral at that specific ore grade can be found in literature. Empirical data of energy consumption as a function of ore grade suggest relationships varying from x_{m}^{-02} to x_{m}^{-09} (Valero et al., 2013). This equation is a very rough approximation, but it is closer to the actual mining behavior than the one proposed by Chapman & Roberts (1983).

Table 4. Exergy replacement costs (ERC) of selected minerals (Valero & Valero, 2014). If not specified, values are expressed in GJ/t of substance.
x_c, ore grade in Thanatia; x_m, average ore grade in the mine; x_r, pre-smelting ore grade; *k*, unit exergy cost; *ERC*, exergy replacement costs.

Substance	E(x)	x_c(g/g)	x_m(g/g)	x_r(g/g)	k(x=x_c)	k(x=x_m)	ERC	Mining and conc.	Smelting and refining
Aluminium (Gibbsite)	$E=1,508x^{-0.5}$	1.38E-03	7.03E-01	9.50E-01	2,088	1,041	627.3	10.5	23.9
Antimony (Stibnite)	$E=2.72x^{-0.5}$	2.75E-07	5.27E-02	9.00E-01	3,929	40	474.5	1.4	12.0
Arsenic (Arsenopyrite)	$E=26.3x^{-0.5}$	4.71E-06	2.17E-02	9.00E-01	1,470	63	399.8	9.0	19.0
Beryllium (Beryl)	$E=4.51x^{-0.5}$	3.22E-05	7.80E-02	9.00E-01	362	26	252.7	7.2	450.0
Bismuth (Bismuthinite)	$E=26.3x^{-0.5}$	5.10E-08	2.46E-03	9.00E-01	7,859	94	489.2	3.6	52.8
Cadmium (Greenockite)	$E=26.3x^{-0.5}$	1.16E-07	1.28E-04	3.86E-03	39,230	3,609	5,898.4	263.9	278.5
Chromium (Chromite)	$E=11.81x^{-0.5}$	1.98E-04	6.37E-01	8.10E-01	48	18	4.5	0.1	36.3
Cobalt (Linnaeite)	$E=2.24x^{-0.64}$	5.15E-09	1.90E-03	4.56E-02	-	-	10,871.9	9.2	129.0
Copper (Chalcopyrite)	$E=23.81x^{-0.35}$	6.64E-05	1.67E-02	8.09E-01	525	170	110.4	28.8	21.4
Fluorite	$E=7.25x^{-0.5}$	1.12E-05	2.50E-01	9.00E-01	582	25	182.7	1.5	-
Gold	$E=135,664x^{-0.285}$; x [g/t]	1.28E-09	2.24E-06	1.38E-04	6,380,357	2,135,879	583,668.4	10,7751.8	-
Gypsum	$E=3.58x^{-0.5}$	1.26E-04	8.00E-01	9.50E-01	118	35	15.4	0.2	-
Iron ore (Hematite)	$E=3.58x^{-0.5}$	9.66E-04	7.30E-01	9.50E-01	165	78	17.7	0.7	13.4
Lead (Galena)	$E=3.58x^{-0.5}$	6.67E-06	2.37E-02	6.35E-01	384	21	36.6	0.9	3.3
Lime	$E=3.58x^{-0.5}$	8.00E-03	6.00E-01	9.50E-01	13	9	2.6	0.4	5.8
Lithium (Spodumene)	$E=3.58x^{-0.5}$	3.83E-04	8.04E-01	9.50E-01	190	88	545.8	12.5	420.0
Manganese (Pyrolusite)	$E=0.911x^{-0.5}$	4.90E-05	5.00E-01	6.71E-01	37	8	15.6	0.2	57.4
Mercury (Cinnabar)	$E=96.8x^{-0.5}$	5.73E-08	4.41E-03	9.00E-01	209,116	2,154	28,297.9	157.0	252.0
Molybdenum (Molybdenite)	$E=23.6x^{-0.5}$	1.83E-06	5.01E-04	9.18E-01	6,505	660	907.9	136.0	12.0
Nickel (sulphides) Pentlandite	$E=17.01x^{-0.67}$	5.75E-05	3.36E-02	4.68E-01	13,039	585	761.0	15.5	100.0
Nickel (laterites) Garnierite	$E=2.11x^{-0.5}$	4.10E-06	4.42E-02	8.04E-02	876	136	167.5	1.7	412.0
Phosphate rock (Apatite)	$E=0.373x^{-0.5}$	4.03E-04	5.97E-03	9.00E-01	77	29	0.3	0.3	4.6
Potassium (Sylvite)	$E=15.4x^{-0.5}$	2.05E-06	3.99E-01	9.00E-01	1,926	45	1,224.2	3.1	N.A.
Silicon (Quartz)	$E=3.97x^{-0.5}$	2.29E-01	6.50E-01	9.80E-01	6	9	0.7	0.7	76.0
Silver (Argentite)	$E=24.7x^{-0.5}$	1.24E-08	4.27E-06	9.00E-01	112,846	8,813	7,371.4	1,281.4	284.8
Sodium (Halite)	$E=8.13x^{-0.5}$	5.89E-04	2.00E-01	9.00E-01	71	14	44.0	3.3	39.6
Tantalum (Tantalite)	$E=429x^{-0.5}$	1.58E-07	7.44E-03	3.80E-01	6,729,367	111,449	482,827.9	3,082.8	8.1
Tin (Cassiterite)	$E=10.6x^{-0.5}$	2.61E-06	6.09E-03	8.63E-01	2,704	133	426.3	15.2	11.4
Titanium (Ilmenite)	$E=8.16x^{-0.5}$	4.71E-03	2.42E-02	9.00E-01	172	105	4.5	7.2	128.1
Titanium (Rutile)	$E=6.32x^{-0.5}$	2.73E-04	2.10E-03	9.00E-01	143	67	8.8	13.8	243.8
Uranium (Uraninite)	$E=138.8x^{-0.28}$	1.51E-06	3.18E-03	7.50E-01	13,843	3,697	901.4	188.8	N.A.
Vanadium	$E=1.92x^{-0.5}$	9.70E-05	2.00E-02	9.00E-01	4,174	632	1,055.3	136.0	381.0
Wolfram (Scheelite)	$E=1.61x^{-0.5}$	2.67E-06	8.94E-03	9.00E-01	69,721	3,033	7,429.3	213.0	381.0
Zinc (Sphalerite)	$E=3.01x^{-0.5}$	9.96E-05	6.05E-02	7.90E-01	104	13	24.8	1.5	40.4
Zirconium (Zircon)	$E=3.01x^{-0.5}$	3.88E-04	4.02E-03	9.00E-01	10,580	4,538	654.4	738.5	633.0

Table 4 shows a summary of the exergy replacement costs (ERC), mining, concentration and refining costs of selected non-fuel minerals (Valero & Valero, 2014). Additionally this table shows the ore grades in Thanatia, the mine and pre-smelting grade (x_c, x_m and x_r respectively).

As stated before, each substance is extracted only from one mineral ore, showed in parenthesis. The values of k(x=x_c) and k (x=x_m) are of special interest, as k (x=x_c), multiplied by the minimum exergy required to concentrate the mineral from the crust to the mine, represents the amount of energy required to mine and concentrate the substance from Thanatia to the current conditions found in Nature.

Exergy replacement costs provide a measure of irreversibility, as they are calculated as the ratio between the real energy required for mining and concentration and the minimum thermodynamic energy requited to achieve this same process. They 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/ton. If we look at scarcer minerals, such as gold or mercury, these values are 583,668 and 28,298 GJ/ton respectively. These numbers can provide hints of which minerals would be the most complicated to replace hence also placing focus on quality minerals.

Still, this is only one part of the equation, and to have a better understanding of mineral depletion, along with exergy replacement costs, other parameters must be taken into account. Exergy replacement costs together with mining, beneficiation, smelting and refining costs, can be used to measure the thermodynamic rarity of mineral resources. If technology does not change, the thermodynamic rarity of a given mineral will remain constant as it only depends on a fixed initial (x_c) and final (x_b) state, x_c corresponding to the ore grade in Thanatia and x_b to the ore grade after the beneficiation process (Figure 13).

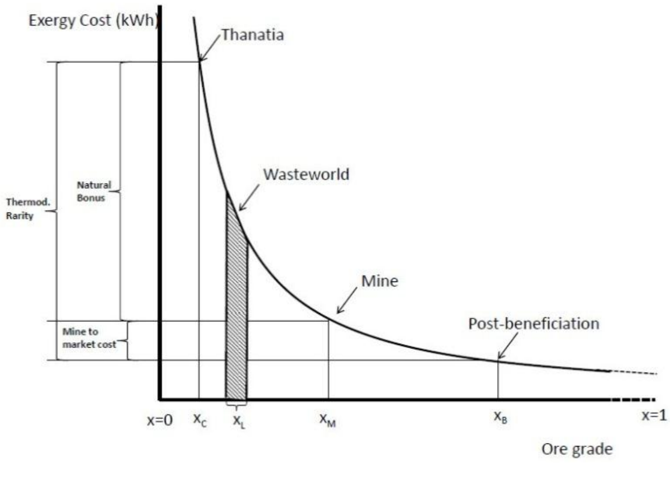

Figure 13. Thermodynamic rarity; x_c, x_m and x_b represent the ore grades in Thanatia, the mines and post-refining respectively (Valero & Valero, 2014).

In other words, thermodynamic rarity is the sum of a real cost, accounting for the actual amount of resources needed to convert a mineral into a commodity, and a hidden cost, the free natural bonus for having the minerals concentrated in the crust in mines. That said, thermodynamic rarity can be defined as the amount of exergy resources needed to obtain a mineral commodity from Thanatia to the market conditions, using the best available technology (Valero & Valero, 2015).

Additionally it also varies from mineral to mineral, as it is a function of its absolute scarcity in Nature and the state of technology. Thermodynamic rarity can also unify the notions of resources and reserves data (recoverable, unrecoverable, proved, indicated, inferred, etc.), typically used by the geological surveys services, as all these concepts are located in a specific interval of ore grade.

1.8. MAIN OBJECTIVES OF THIS THESIS AND THEMATIC UNIT

Physical Geonomics was first developed in the book "*Desarrollo económico y deterioro ecológico*" (Economic Development and Ecological Deterioration) by Naredo and Valero (1999), where the bases of the general theory were proposed. Thereafter several PhD thesis were written expanding the exergoecology approach, being the first one "*Análisis de los costes exergéticos de la riqueza mineral terrestre*" (Exergetic analysis of the costs of the Earth's mineral wealth) (Ranz, 1999). In Ranz's PhD thesis an approximation of the reference environment was proposed and the concept of exergy replacement costs was introduced. Subsequently, one year later "*Valoración exergética de recursos naturales, minerales, agua y combustibles fósiles*" (Exergetic evaluation of natural resources, minerals, water and fossil fuels) (Botero, 2000), expanded the exergy analysis to natural resources such as water and fossil fuels, additionally carrying out a first approximation for the exergy replacement costs of several substances.

In the last few years two more PhD theses have developed more aspects of the Physical Geonomics methodology. First Alicia Valero (2008) consolidated the basis of Thanatia, a conceptual model of the Earth where all non-fuel minerals have been extracted and dispersed and where all fossil fuels have been burnt, that can be used as a reference for the physical quantification of the depletion of resources. Alicia Valero additionally conducted an assessment of the physical stock and the degradation velocity of the mineral resources due to human action using the exergoecological approach. She calculated the thermodynamics properties of the Earth and the exergy of the mineral resources and analyzed the mineral degradation during the 20th century to estimate peak of production of selected substances. Afterwards, Rosa Adriana Domínguez (2014) applied the exergy analysis to mining and metallurgical processes, studying the technologies and exergy consumption associated with the mining and metallurgical industry and analyzing the influence of technological learning and declining ore grades on energy consumption.

A general overview of depletion of mineral resources at global scale using exergy indicators was already carried out in previous studies as well as punctual analysis concerning the mining process of selected substances (Domínguez et al., 2013; Valero et al., 2008; Valero, Valero, & Domínguez, 2011; Valero & Valero, 2010, 2012b; Valero, 2008; Valero & Valero, 2011).

Following this research line, the main objective of this PhD Dissertation has been the validation and improvement of the methodology, obtaining more accurate values of exergy replacement costs based on real energy use in the mining industry and observing the evolution of energy consumption, ore grade and production over time. Additionally, the Physical Geonomics methodology has been applied at the macro-scale level using several case studies, analyzing mineral trade and depletion from a local and regional point of view.

The achievement of this overall objective has led to a completion of various tasks which are cited below:

- Bibliographic review
- Refine and improve the methodology analyzing real data on energy use and energy intensity in the mining industry for selected metallic minerals (Chapter 2 → *paper under preparation*)
- Analyze trends of ore grade, energy consumption and production over time (Chapter 2)
- Propose global indicators to evaluate resource efficiency (Chapter 3 → **Paper I**: *Using thermodynamics to improve the resource efficiency indicator GDP/DMC*)
- Create a link between Ecological Economics and Physical Geonomics (Chapter 4 → **Paper II***: How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study.)*
- Validate the methodology with different case studies at the macro-scale (Chapter 5):
    - Thermodynamic assessment of mineral depletion and trade in Spain → **Paper III**: *An exergoecological analysis of the mineral economy in Spain*
    - Assessment of European (EU-28) mineral trade → **Paper IV**: *Material flow analysis for Europe: an exergoecological approach*
    - Comparative analysis between an importing and an exporting country *(paper pending from publishing)*

2. ENERGY USE IN THE MINING INDUSTRY

As stated before, energy use in the mining industry plays a major role in the overall energy consumption. Performing a thorough analysis of the energy intensity and the changes in energy demand as a function of the ore grade becomes fundamental.

Therefore, in this section an analysis of the energy consumption over time for selected mines over the world has been accomplished, as well as an analysis of the evolution of the ore grade. For this endeavor, information regarding electricity consumption, diesel use, total energy consumption and average ore grade per year has been compiled. The principal aim has been to observe the general tendencies of all of these factors as well as to validate and improve the Physical Geonomics theory using empirical data to recalculate exergy replacement costs of different substances. A total of 40 mines have been selected that extract gold, silver, copper, lead and zinc among other metallic minerals.

2.1. METHODOLOGY

Despite the fact that the mining sector is not known for being very transparent when information related to energy use is involved, during the past decade many mining companies have started to report annually their sustainability and social performance along with their financial results. These reports vary substantially from one company to another but can be used as an approach to have real information on their performance and to analyze possible links between energy consumption, ore grade, mineral production, greenhouse gas emissions, solid wastes, among others.

To have empirical information on energy use in the mining industry, first a preliminary analysis of several mines and companies has been accomplished to select the ones that provide both reliable and disaggregated information. Overall, of the more than fifty mines that have been analyzed, only a total of 40 mines have been selected, trying to take into account only those whose reports were more accurate, reliable and which provided more disaggregated data. Eventually, data has been sourced from numerous companies' annual reports, as well as sustainability and financial reports over several years. All the companies and report types are presented in Table 5.

Table 5. List of reports reviewed and analyzed.

Report types	**Years**	**Company**
Sustainability reports	2002-2014	AngloAmerican
Annual reports; sustainability reports	2005-2014	Antofagasta Minerals
Sustainability reports	2006-2012	Barrick
Annual reports; sustainability reports	2005-2014	BHP Billiton
Sustainability reports	2000-2014	CODELCO
Annual reports; sustainability reports	2009-2013	First Quantum Minerals
Sustainability reports	2006-2013	Goldfields
Sustainability reports	2000-2007	Río Tinto
Financial reports; sustainability reports	2007-2014	Lundin Mining
Annual reports; sustainability reports	2008-2013	Milpo
Financial reports; sustainability reports	2009-2014	MMG Limited
Annual reports; sustainability reports	2006-2014	New Crest Mining Limited
Financial reports; sustainability reports	2008-2014	Oz Minerals
Annual reports; sustainability reports	2001-2014	Xstrata-Glencore

Following the information available on the reports of the aforementioned companies, the following data has been compiled when possible for each year and for each individual mine:

- Ore mined and milled
- Contained mineral or metal production

- Average ore grade
- Electricity and diesel use
- Waste rock mined
- Tailings
- GHG emissions
- Water use

The quality and consistency of the data in the reports varied significantly between companies and even between years. Some of the companies have already adopted the Global Reporting Initiative (GRI) protocol, a coalition of the United Nations, industry, government and civil society groups (GRI, 2006). The aim is to provide guidelines to achieve uniform and consistent reports on sustainability performance for different sectors, including mining and metals (GRI, 2011). The main drawback is that they only require general data regarding different social, economic and environmental aspects. For example, a company that has several mines in operation can provide only an aggregated data for the energy consumed within all the owned mines, fulfilling the requirements of the GRI but at the same time giving little and limited information.

The list of the 40 selected mines, with information of the main metal extracted, mine type and process can be found in Table 6. Each mine site has been categorized based on the major mining and extraction methods used, separating underground (UG), open cut (OC) and mixed mines. The main methods differentiated in the mining process are mine (M), concentration (C), smelting (S), refining (R) and leaching (L).

Table 6. Mines considered in the study.
UG= underground, OC= open cut; M= mine; C= concentration; S=smelting; R= refining; L=leaching.

Mine	**Company (as of year 2014)**	**Main metals extracted**	**Mine type**	**Mine process**
Australia				
Granny Smith	Gold Fields	Au	Mixed	MCL
Agnew	Gold Fields	Au	Mixed	MCL
St Ives	Gold Fields	Au	Mixed	MCL
Darlot	Gold Fields	Au	UG	MCL
Cadia Valley	New Crest Mining Limited	Cu-Au	Mixed	MC
Ernest Henry	Glencore	Cu-Au	OC	MC
Mount Isa (Cu)	Glencore	Cu-Ag	UG	MCS
Osborne	Barrick	Cu-Au	Mixed	MC
Prominent hill	Oz Minerals	Cu-Ag	OC	MC
Olympic Dam	BHP Billiton	Cu-U-Ag-Au	UG	MCSRL
Telfer	New Crest Mining Limited	Cu-Au	Mixed	MC
Cannington	Glencore	Pb-Ag	UG	MC
McArthur River	Glencore	Zn-Pb	Mixed	MC

Mine	Company (as of year 2014)	Main metals extracted	Mine type	Mine process
Mount Isa (Zn)	Glencore	Zn-Pb-Ag	Mixed	MCS
Century	MMG Limited	Zn-Pb-Ag	OC	MC
Golden Grove	MMG Limited	Zn-Cu-Ag-Au	UG	MC
Rosebery	MMG Limited	Zn-Pb-Cu-Ag-Au	UG	MC
Chile				
Mantos Blancos	AngloAmerican	Cu	OC	MCSL
El soldado	AngloAmerican	Cu	Mixed	MCL
Mantoverde	AngloAmerican	Cu	OC	ML
El Tesoro	Antofagasta Minerals	Cu	OC	MCL
Michilla	Antofagasta Minerals	Cu	Mixed	MCL
Escondida	BHP Billiton	Cu	UG	MCL
Radomiro Tomic	CODELCO	Cu	OC	MCL
Collahuasi	AngloAmerican and Glencore	Cu-Mo	OC	MCL
Los pelambres	Antofagasta Minerals	Cu-Mo	OC	MCL
Chuquicamata	CODELCO	Cu-Mo	OC	MCSL
Los bronces	AngloAmerican	Cu-Mo	OC	MCSL
División Andina	CODELCO	Cu-Mo-Ag	Mixed	MC
Salvador	CODELCO	Cu-Mo-Ag-Au	Mixed C	MSCL
El teniente	CODELCO	Cu-Mo-Ag-Au	UG	MCS
Laos (LPDR)				
Sepon	MMG Limited	Cu-Au	OC	ML
Peru				
El porvenir	Milpo	Zn-Pb-Cu	UG	MC
Cerro Lindo	Milpo	Zn-Pb-Cu	UG	MC
Antamina	BHP Billiton and Glencore	Zn-Cu-Mo (Ag, Pb)	OC	MCL
Portugal				
Neves-Corvo	Lundin Mining	Zn-Pb-Cu-Ag	UG	MC
Spain				
Aguablanca	Lundin Mining	Ni-Cu	OC	MC
Las Cruces	First Quantum Minerals Ltd.	Cu	OC	MCL
Sweden				
Zinkgruvan	Lundin Mining	Zn-Pb-Cu-Ag	UG	MC
United States				
Bingham Canyon	Río Tinto	Cu-Au	OC	MCSR

With the information available, several energy intensity factors have been calculated as follows:

a) Electricity use (kWh per tonne of total ore mined) as a function of ore grade
b) Liters of diesel per tonne of rock (including tailings, waste rock and ore) as a function of ore grade

Moreover, the evolution of the ore grade over the years has been analyzed for each mine as well as the dependency of the energy intensity according to the type of the mine and process. The main goal with this first task is to improve the methodology obtaining real energy consumption data as a function of ore grade for several metallic commodities and compare them, when available, with other studies and reports. Besides, the total energy consumption as a function of the mineral produced has been analyzed for the case of copper to observe the relationship between declining ore grades, energy and production.

In addition, to improve the methodology and the exergy replacement costs available data, it is also fundamental completing the study calculating the exergy replacement costs of other substances that were not included before in the analysis. This is the case of gallium, germanium and indium, metals that have a major role in new technologies. Indium, for instance, is used in flat panel televisions and touch screens, while gallium and germanium are used in solar cells. Moreover, these three metals were identified as critical by the European Commission, stating that the forecast average demand growth to 2020 was very strong for gallium (more than 8% growth per year), strong for indium (from 4.5 to 8%) and moderate for germanium (from 3 to 4.5%) (European Commission, 2014). Therefore, to have an approximation, the exergy replacement costs of gallium, germanium and indium have been calculated in this PhD based on the concentration in the main ores of which they are extracted.

2.2. ENERGY INTENSITY USE

The main goal of this analysis has been focused on obtaining information of energy consumption as a function of ore grade, as well as to have a better knowledge of energy intensity use in mining. For this task, the following substances have been included in this study: gold, silver, copper, lead, zinc and nickel. As countries such as Chile, Australia and Peru have been incorporated in the study, approximately between 30-40% of the global copper production is being taken into account, as well as half of the Australian gold production.

Using each mining company’s annual reports, sustainability and financial reports over the years, information regarding energy use, among other factors already mentioned, has been compiled. For the vast majority of the mines, the reports comprise the years 2005 to 2014, but for some mines the information available can go back to the early nineties.

It is noteworthy that, even if many of the analyzed mines are adhering to the Global Reporting Initiative (GRI), a global and independent organization that provides tools to other organizations to communicate their impacts on the environment, different reports does not always reflect the information the same way. Sometimes the information is disaggregated by mines or processes, sometimes providing the general information for the whole company, and even the way the data are reported can change from year to year.

Data of average intensity use of energy per mine, meaning the average kWh per tonne of ore mined or milled as well as the average liters of diesel used per tonne of rock moved are represented in Table 7.

Table 7. Average energy intensity use for selected mines.

Mine type: OC- open cut; UG – Underground, Mixed represents a mine that has both underground and open cut facilities. Process: M – Mine, C – Concentrator, S – Smelter, R – Refinery, L – Leaching. For kWh/t ore and L diesel/t rock the average number is provided as well as the standard deviation, the number in brackets represents the number of data points for each mine.

Mine	Metals	Mine type	Mine process	Average kWh/t ore	Average L diesel/t rock	Period reported
Australia						
Granny Smith	Au	Mixed	MCL	199 ± 141 (18)	2.5 ± 1.9 (18)	1989-2013
Agnew	Au	Mixed	MCL	43 ± 14 (14)	0.6 ± 0.4 (5)	1991-2009
St Ives	Au	Mixed	MCL	31 ± 6 (14)	1.5 ± 0.6 (6)	1991-2009
Darlot	Au	UG	MCL	80 (1)	-	1993-2007
Cadia Valley	Cu-Au	OC	MS	53 ± 4 (6)	-	2004-2009
Ernest Henry	Cu-Au	OC	MC	49 ± 7 (6)	-	1998-2007
Mount Isa (Cu)	Cu-Ag	UG	MCS	81 ± 34 (6)	1.1 (1)	2005-2012
Osborne	Cu-Au	Mixed	MC	-	-	
Prominent Hill	Cu-Ag	OC	MC	64 ± 25 (6)	0.5 ± 0.2 (6)	2009-2014
Olympic Dam	Cu-U-Ag-Au	UG	MCSRL	107 ± 23 (17)	2.8 ± 0.6 (17)	1991-2014
Telfer	Cu-Au	Mixed	MC	124 ± 13	-	2005-2009
Cannington	Pb-Ag	UG	MC	-	-	2007
McArthur River	Pb-Zn	Mixed	MC	60 ± 5 (5)	-	2006-2010
Mount Isa (Zn)	Zn-Pb-Ag	Mixed	MCS	-	-	2006-2012
Century	Pb-Zn-Ag	OC	MC	120 ± 35 (7)	-	2009-2014
Golden Grove	Zn-Cu-Ag-Au	UG	MC	55 ± 7 (7)	-	2009-2014
Rosebery	Pb-Zn-Cu-Ag-Au	UG	MC	62 ±12 (7)	-	2009-2014
Chile						
Mantos Blancos	Cu	OC	MCSL	15 ± 3 (10)	-	2002-2014
El soldado	Cu	Mixed	MCL	28 ± 7 (11)	0.4 ± 0.2 (4)	2002-2014
Mantoverde	Cu	OC	ML	12 ± 2 (11)	0.7 ± 0.8 (4)	2002-2014
El Tesoro	Cu	OC	MCL	31 ± 7 (7)	0.3 ± 0.1 (5)	2007-2014

Mine	**Metals**	**Mine type**	**Mine process**	**Average kWh/t ore**	**Average L diesel/t rock**	**Period reported**
Michilla	Cu	Mixed	MCL	34 ± 2 (5)	0.5 ± 0.2 (4)	2007-2014
Escondida	Cu	UG	MCL	31 ± 13 (12)	0.7 ± 0.3 (12)	2001-2014
Radomiro Tomic	Cu	OC	MCL	13 ±1 (3)	1.5 (1)	2011-2013
Collahuasi	Cu-Mo	OC	MCL	20 ± 1 (10)	1.4 ± 1.1 (10)	2002-2014
Los pelambres	Cu-Mo	OC	MCL	27 ± 10 (8)	0.4 ± 0.1 (8)	2007-2014
Chuquicamata	Cu-Mo	OC	MCSL	46 ± 1 (3)	1.2 ± 0.2 (2)	2000-2013
Los bronces	Cu-Mo	OC	MCSL	20 ± 8 (11)	0.9 ± 0.6 (7)	2002-2014
División andina	Cu-Mo-Ag	Mixed	MC	25 ± 3 (12)	1.9 ± 2.2 (9)	2001-2013
Salvador	Cu-Mo-Ag-Au	Mixed	MSCL	34 ±6 (12)	0.8 ±0.3 (9)	2001-2013
El Teniente	Cu-Mo-Ag-Au	UG	MCS	39 ± 4 (12)	-	2001-2013
Laos (LPDR)						
Sepon	Cu-Au	OC	ML	100 ± 40 (7)	2.3 ± 0.8 (4)	2008-2014
Peru						
El Porvenir	Pb-Zn-Cu	UG	MC	53 ± 3 (2)	-	2008-2013
Cerro Lindo	Pb-Zn-Cu	UG	MC	29 ± 4 (2)	-	2008-2013
Antamina	Zn-Cu-Mo	OC	MCL	-	-	2006-2012
Portugal						
Neves-Corvo	Pb-Zn-Cu-Ag	UG	MC	71 ± 6 (7)	0.6 ± 0.1 (6)	2007-2014
Spain						
Aguablanca	Ni-Cu	OC	MC	44 ± 12 (7)	0.5 ± 0.1 (5)	2007-2014
Las Cruces	Cu	OC	MCL	-	-	2009-2014
Sweden						
Zinkgruvan	Pb-Zn-Cu-Ag	UG	MC	75 ± 7 (6)	1.0 ± 1.0 (6)	2007-2014
United States						
Bingham Canyon	Cu-Au	OC	MCSR	112 ± 7 (5)	-	2003-2007

The electricity intensity use, kWh/t ore as a function of the ore grade, for all the commodities is represented in Figure 14 and Figure 15.

In the case of Figure 14, there are two distinctive series of data sets, as the copper mines usually have lower average ore grades than the lead-zinc mines. Approximately, the general trend is that the amount of electricity used per tonne of ore mined in open cut and underground mines increases when the ore grade decreases, as represented by the “general trend” curve. In the case of mixed mines, mines that have both underground and open cut facilities (represented in grey in the figure), the tendency is not that clear but this could be easily explained by the way each mine reports their data as the energy consumption can drastically vary from one mine type to another. Usually, underground mines (represented in the figure in black) are more intensive in energy because of mine depth and ventilation (Northey et al., 2013). In this case this relationship is not so apparent but there are many other factors that could be influencing this, from each individual process to the equipment used on each mine.

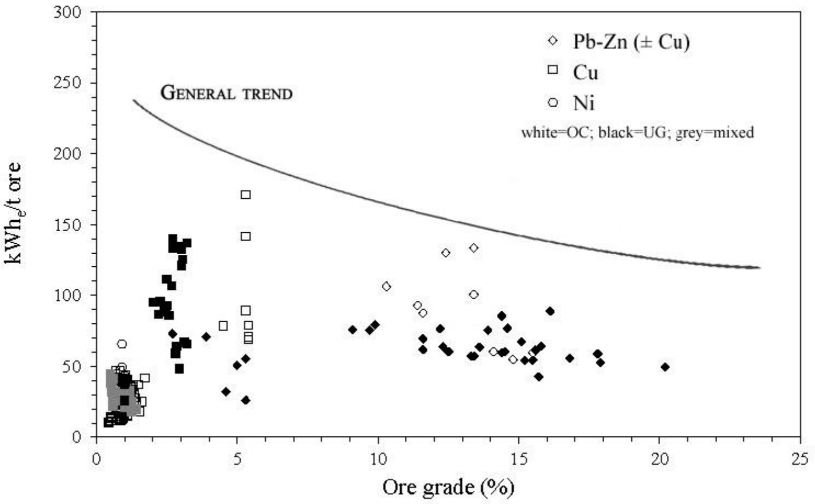

Figure 14. Electricity use (in kWh per tonne of ore) as a function of ore grade (in %); each data point represents a year of production of a mine site.

In the case of Figure 15, only information related to Australian gold mines is represented with the average ore grade measured in grams per tonne.

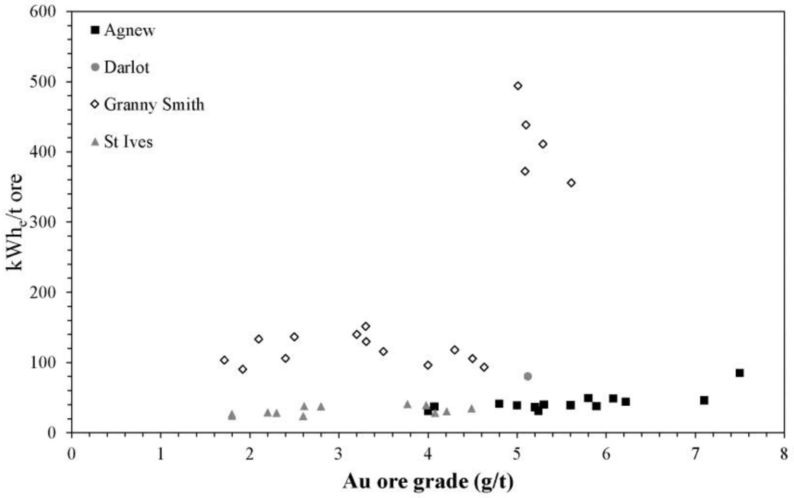

Figure 15. Electricity use (in kWh per tonne of ore) as a function of gold ore grade (in g/t); each data point represents a year of production of a mine site.

Data seem quite dispersed when observing only the ore grade variations but the electricity requirements remains approximately within the same levels, between 25 and 150 kWh/t ore. There is an exception with the *Granny Smith* mine, which clearly shows two totally different sets of data points. In 2007 the mine changed from an open cut mine only to an underground mine only, the energy use being higher in the latter case. The open cut mine had requirements of 116 kWh/t ore while the underground mine has requirements of 414 kWh/t ore as average, almost four times higher. This explains why the *Granny Smith* mine data are so different from one another. In the case of these gold mines, the relationship of energy consumption and ore grade could be approximated to a straight line instead of the exponential tendency that has been shown in other studies (Mudd, 2007b). One explanation could be that only a small number of mines with high gold concentrations were taken into account in this study and that more information should be used to have a better representation.

Another issue that can be analyzed with the data reported by the mining companies is the influence of the mining process and configuration in the electricity use per tonne of ore mined (Figure 16). Mines that extract lead-zinc usually have a MC configuration (mine + concentrator) and consume less electricity per tonne of ore, while copper mines tend to have leaching (L) and smelting (S) facilities as well and have higher electricity consumption. On the other hand, mines that have concentrator, leaching and smelter (MCL and MCSL), appear concentrated in the lower left corner as they are usually copper mines with low ore grades. There is only one mine that has a ML configuration (mine + leaching), which is the *Sepon* mine (LPDR), and as the mining process is quite particular the data regarding electricity use appear vertically scattered while the ore grade remains within the same numbers. Again, the general trend seems to be that the lower the ore grade in the mine, the higher the electricity consumption per tonne of ore mined is, especially in the case of mines that have a MC, MCS and MCSRL configuration.

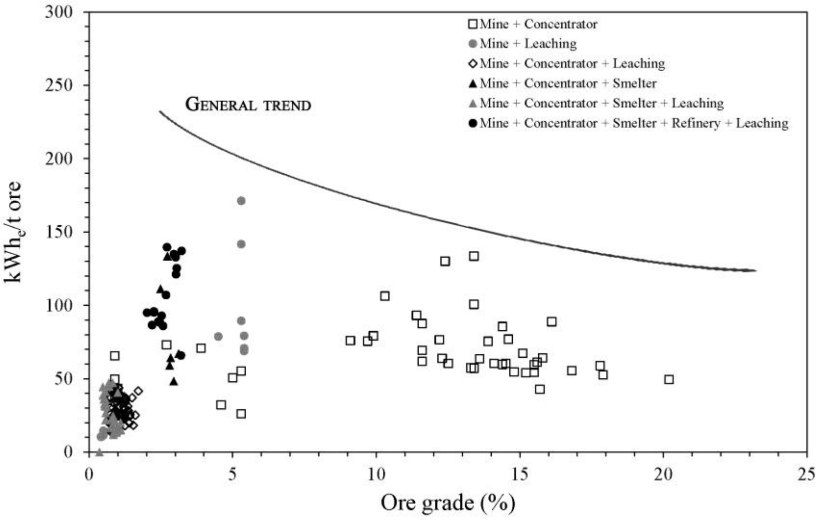

Figure 16. Electricity intensity (in kWh/t ore) as a function of ore grade (in %) represented by process configuration, each data point represents a year of production of a mine site.

Diesel intensity use is represented in Figure 17 as a function of the ore grade. Again, information of copper, lead, zinc and nickel mines is represented, distinguishing between open cut, mixed and underground mines. As the mining reports vary considerably regarding this issue, it has not been possible to obtain as many as values as for electricity intensity use, but it can still be used to have an overall picture of the diesel consumption. Usually diesel is used in mines for transport and machinery and for electricity production. In the case of diesel used for transport there are two main distinctions, diesel used for transport inside the mine and diesel used for transport outside the mine. Overall, it seems that the lower the ore grade, the higher the diesel consumption is, and this confirms the patterns observed in similar studies (Northey et al., 2013). There are several scattered data that does not show this tendency, but this again could be explained by the way each mine reports the information on diesel use.

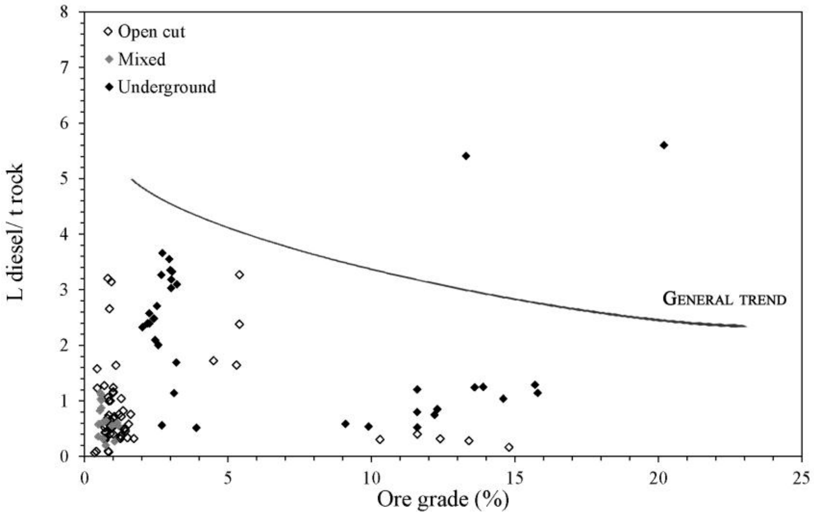

Figure 17. Diesel intensity (in L diesel/t rock) as a function of ore grade (in %) by mine type, each data point represents a year of production of a mine site.

2.3. ORE GRADE AND ENERGY CONSUMPTION

One straightforward information that can be obtained with the average ore grade data reported by the mining companies is the variation of ore grade over time. In this case, the analysis has been centered in copper mines as there is more reliable and representative information available (Figure 18).

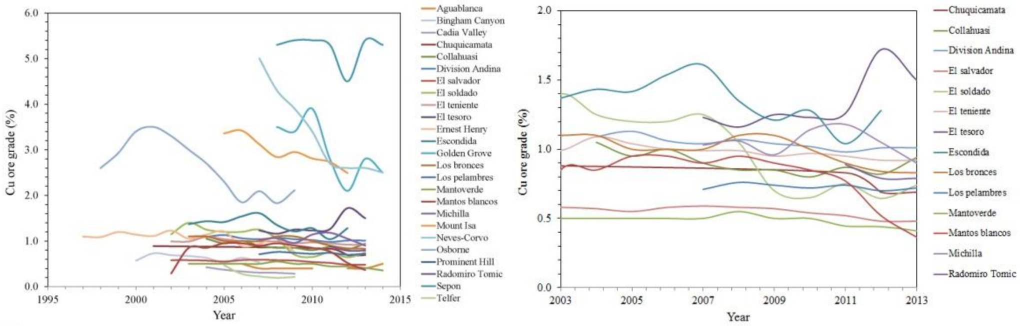

Figure 18. Right: Evolution of copper ore grade for selected mines over the years. Left: Evolution of copper ore grade for selected Chilean mines from 2003 to 2013.

In general, a decrease of the average ore grade per year can be appreciated, whether the mine has a high initial copper ore grade, such as *Sepon* (LPDR) or *Neves-Corvo* (Portugal), or a lower copper ore grade, such as *Aguablanca* (Spain), *Telfer* (Australia) *or El Tesoro* (Chile). For example, *Century* (Australia) had an average zinc ore grade of 13.3% in 2008 and in 2014 the average ore grade was only 9.7%.

As the Chilean mines have lower average ore grades than the rest of the mines taken into account in this study, their trends can be analyzed separately (Figure 16, left). Even if there are some variations, it can be stated that, from 2003 to 2013, the ore grade decreased an average of 28.8%. The biggest decrease of copper ore grade corresponded to the copper oxides extracted in *El soldado* mine, going from 1.7% to 0.6% in just ten years, followed by *Michilla* and *Mantos Blancos*, with a decrease of ore grade of 39 and 37% respectively.

As stated before, as mines with higher average ore grade have already been processed, the average ore grade for most metals is currently much lower. The data presented here are consistent with other studies regarding evolution of copper ore grade over time (Northey et al., 2013, 2014; Swart & Dewulf, 2013b) and can be extrapolated to other metallic minerals.

In Australia, the average ore grade for several metallic substances has been continuously decreasing over time (Figure 19). Being the case of copper and gold the most striking ones as between 1857 and 2010 the ore grades have decreased 93.4% and 96.7% respectively. This historical trend is consistent with the most recent data presented in this dissertation.

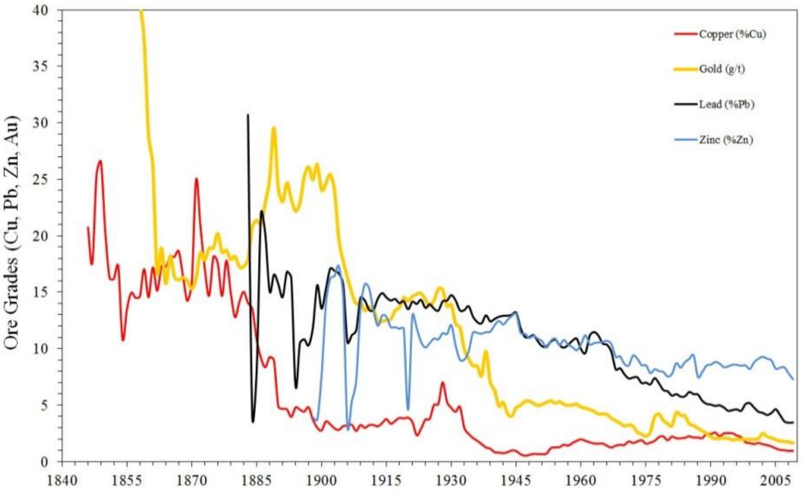

Figure 19. Historical trends of average ore grade for selected substances in Australian mines (modified from Mudd, 2010b).

Additionally, the average ore grade as a function of the yearly production of copper can be represented (Figure 20). One interesting conclusion that can be drawn from this analysis is that the production in mines with higher ore grades, such as *Sepon (LPDR)*, *Osborne* (Australia) or *Mount Isa* (Australia), is much lower when compared to low ore grade mines, such as *Bingham Canyon* (United States) or *Escondida* (Chile).

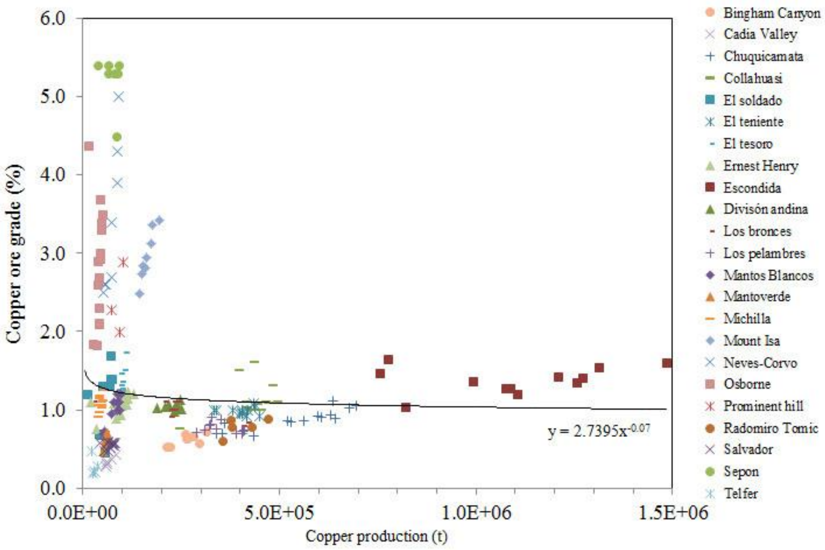

Figure 20. Copper ore grade as a function of copper production for selected mines; each data point represents a year of production of a mine site.

Another relevant aspect that can be observed is the tendency of the total energy consumption in the 25 mines taken into account in this study and its relationship with the tonnes of total copper produced (Figure 21).

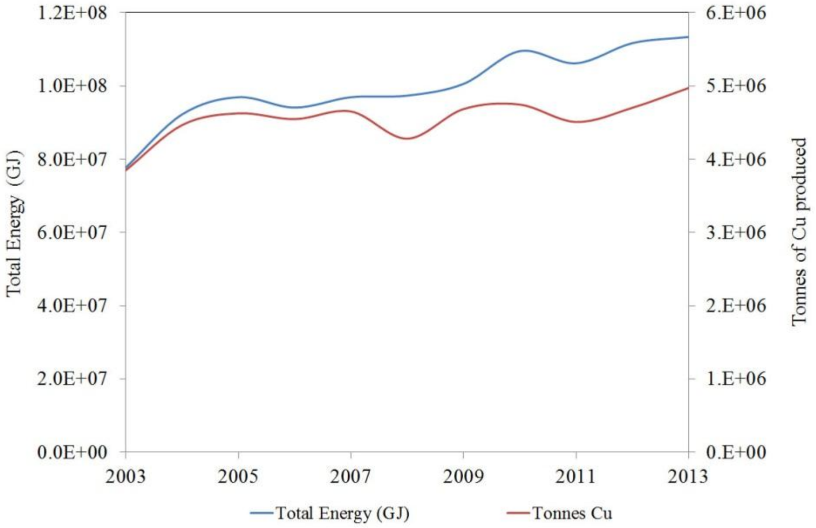

Figure 21. Evolution of the total energy (GJ) and tonnes of copper produced for selected mines from 2003 to 2013.

The total energy consumed in these copper mining projects as well as the tonnes of copper produced clearly increases over time. In the case of energy consumption, there is a 46% increase from 2003 to 2013, and a 30% increase of copper produced. This is linked to the exponential increase of total material extraction that can be observed at global level, as more energy is needed to produce the minerals to meet society demand. Additionally, the decrease in ore grades observed before for those same mines also entails an increase in energy consumption, as more waste rock needs to be extracted to produce the same amount of ore. Therefore, energy consumption, ore grade and production are closely linked and they strongly depend on each other.

Using the same example of copper, the Australian mega-trends have been extensively studied (Mudd, 2010b), additionally linking the energy consumption and the production to the amount of waste rock generated (Figure 22). Again it is logical, as the more copper you need to meet the demand, more waste rock is removed and more energy is needed for that task.

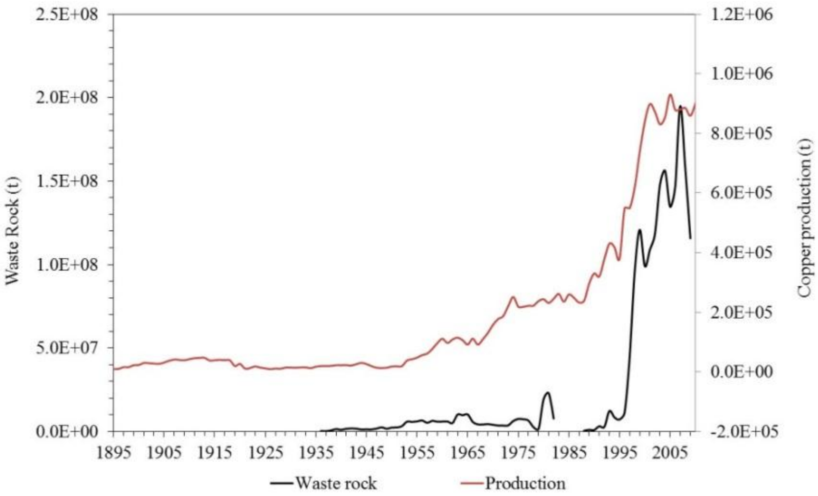

Figure 22. Evolution of Australian copper production and associated waste rock (modified from Mudd, 2010b).

2.4. EXERGY ANALYSIS

With the data set obtained from the mines reports we can also calculate the total energy used per tonne or ore produced for each metallic mineral (in GJ/t) and compare this information with the theoretical results derived from Equation 7. This analysis has been carried out for copper, gold and zinc to obtain more accurate data of their respective exergy replacement costs.

Additionally, exergy replacement costs for gallium, germanium and indium have been calculated using information on the energy used to produce the main ores were they are extracted.

a) Copper

Global average mined ore grades for copper mines are approximately 0.62% of Cu content, with an annual production of 16 million tonnes per year, being the production of copper in 2014 approximately 18.7 million tonnes (Mudd & Weng, 2012; USGS, 2015a). According to Cox & Singer (1992), the average ore grade in the mine (x_m) is 1.67% and in the case of the 25 copper mines analyzed in the present study, the average ore grade is 1.48%. These 25 mines produced more than 5 million tonnes in 2009, which corresponded to 32% of the total world production that same year (USGS, 2010).

Copper has a crustal concentration of x_c=6.64E^{-05} g/g (Valero, Valero, & Gómez, 2011) and an average ore grade after beneficiation of x_r=28.00 E^{-02} g/g (Kennecott Utah Copper, 2004). The energy requirements for copper mining, taking into account mining and concentration processes, are 66.7 GJ/t (Chapman & Roberts, 1983), being 0.6% the average ore grade. For the smelting and refining processes, the energy requirements are 47 GJ/t, this number can even reach 15 GJ/t in the case of the lowest ore grades when energy-saving technologies have been introduced (Ayres et al., 2002).

Figure 23 shows the trends of energy consumption as a function of the ore grade, along with the theoretical concentration energy (represented in black) and the concentration energy corresponding to the real data sets (represented in red). It can be observed that both show similar trends, with energy consumption increasing when the ore grade decreases.

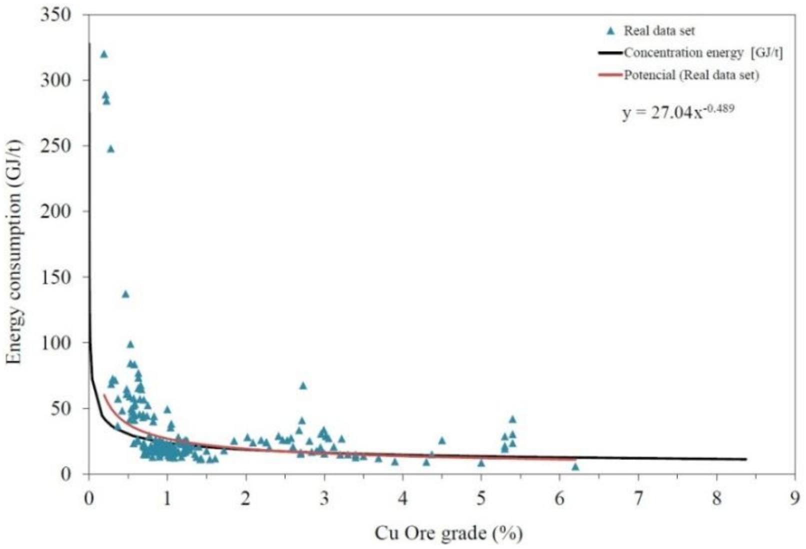

Figure 23. Energy requirements for copper production as a function of the ore grade.

b) Gold

As gold usually appears in lower concentrations, measured in grams per tonne, the average ore grade can change drastically from one mine to another.

Usually open cut mines have lower grades, around 1 to 4 g/t, while underground mines can reach up to 8 to 10 g/t (World Gold Council). Mudd (2007) estimated the average ore grade for Canada, Australia and South Africa, being 7.15, 2.65 and 9.83 g/t respectively. According to Cox & Singer (1992), the average ore grade in the mine (x_m) is 2.24E^{-06} g/g. The gold production in 2014 was 2,860 tonnes, being China, Australia and the United States the main producers (USGS, 2015a).

Gold has a crustal concentration of x_c=1.28^{-09} g/g (Valero, Valero, & Gómez, 2011) and an average ore grade after beneficiation of x_r=1.38 E^{-04} g/g (Domínguez, 2014). As for energy requirements, gold mining typically requires about 0.31 GJ/t ore or 143 GJ/kg of gold produced (Mudd, 2007b).

In Figure 24 new data of the gold mines as well as data from previous papers (Domínguez & Valero, 2013) is represented.

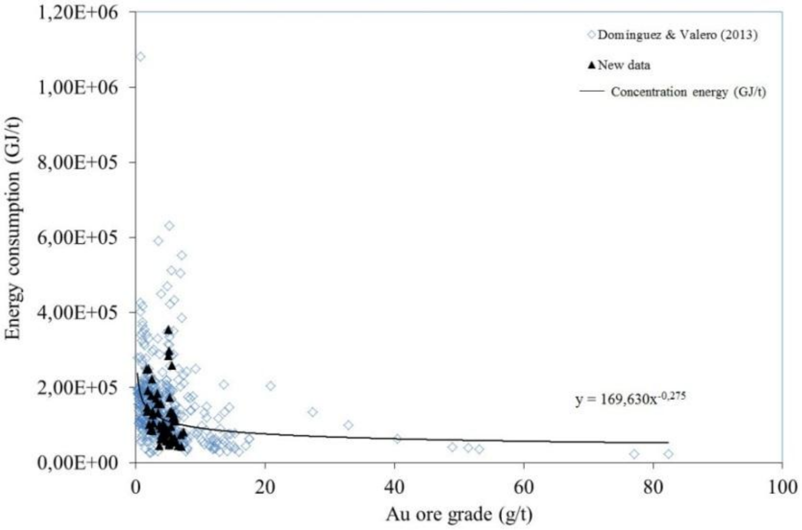

Figure 24. Energy requirements for gold production as a function of the ore grade. Adapted from Domínguez & Valero (2013).

c) Zinc

There is no data available on global average mined ore grades for zinc mines, but the average ore grade in the mine (x_m) estimated by Cox & Singer (1992) is 6.05%, there are also complementary studies regarding the ore grade of specific countries (Mudd, 2009a).

In 2014, 13.3 million tonnes were produced at world level (USGS, 2015a). In the case of the 11 zinc and lead-zinc mines analyzed, the average zinc ore grade is 12.71% and the average lead ore grade is 2.42%. These 11 mines produced more than 1 million ton in 2009, which corresponded approximately to 16% of the total world production that same year (USGS, 2010).

Zinc has a crustal concentration of x_c=9.96^{-05} g/g (Valero, Valero, & Gómez, 2011) and an average ore grade after beneficiation of x_r=7.90E^{-01} g/g (Classen et al., 2007).

As the main metallic mineral extracted in all the mines analyzed is zinc, and lead is extracted as a by-product, it has been assumed that all energy consumed within the mine corresponds to zinc extraction and concentration.

Figure 25 shows the trends of energy consumption as a function of the ore grade, along with the theoretical concentration energy (represented in black) and the concentration energy corresponding to the real data sets (represented in red). Compared to the case of copper, here there is a clear difference between both of them.

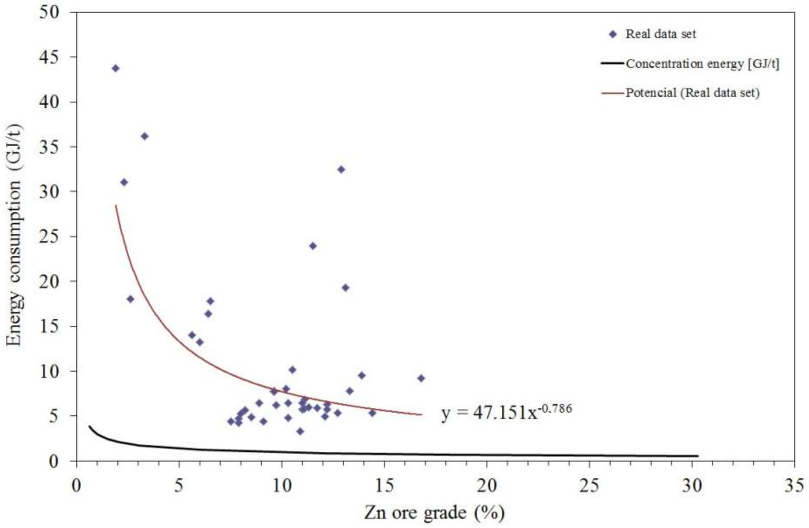

Figure 25. Energy requirements for zinc production as a function of the ore grade.

Table 8 summarizes the results of energy consumption, x_c, x_m, x_r and exergy replacement costs (ERC) of copper, gold and zinc. The values of energy consumption as a function of ore grade for copper, gold and zinc range from $x^{-0.489}$ to $x^{-0.786}$. When comparing these results with other studies, for the case of copper, previous results provided values that are significantly lower, the previous value being $x^{-0.32}$ (Valero, Valero, & Domínguez, 2011). As the information used for the calculations has increased substantially, it seems reasonable to say that the new value of copper is closer to the real situation than the ones obtained before.

Table 8. New values for exergy replacement costs.

Values of x_c, x_m and x_r are referred to the assumed mineral that represents the ores from which the metal is extracted. ERC (1) represents values obtained in previous studies, ERC (2) represents values obtained with this new data.

	E(*x*) [GJ/t]	**x_c [g/g]**	**x_m [g/g]**	**x_r [g/g]**	**ERC [GJ/t] (1)**	**ERC [GJ/t] (2)**
Copper (chalcopyrite)	$E=27.04x^{-0.489}$	$6.64E^{-05}$	$1.67E^{-02}$	$8.09E^{-01}$	110.38	256.82
Gold	$E=169{,}630x^{-0.275}$	$1.28E^{-09}$	$2.24E^{-06}$	$1.38E^{-04}$	583,668	546,057
Zinc (sphalerite)	$E=47.151x^{-0.786}$	$9.96E^{-05}$	$6.05E^{-02}$	$7.90E^{-01}$	24.79	155.03

For the case of zinc, the trends of unit exergy cost and concentration energy show a theoretical value of x^{-1} (Valero, Valero, & Domínguez, 2011). But as the empirical data are usually very limited, when there is no data available $x^{-0.5}$ is used as a general expression. In this case, using real data sets for zinc extraction, the value obtained is $x^{-0.786}$ being a higher value than the theoretical one. In any case, as there is quite dispersion on the data related to energy consumption as a function of ore grade, this new value should only been taken as an approximation.

There is a clear variation of the exergy replacement costs (ERC) for each of these substances. The new value for copper is almost two times higher than the previous one, and this is more striking in the case of zinc, which is six times higher. In the case of gold, the exergy replacement costs, even if it decreases slightly, remain within the same range.

Using this new data, we can calculate *k* ($x=x_c$) and *k* ($x=x_m$) (Table 9). The values of k, multiplied by the minimum exergy required to concentrate the mineral from the crust to the mine, represents the amount of energy required to mine and concentrate the mineral from Thanatia to the current conditions in the mineral deposits. Logically, the values of *k* in the crust (in Thanatia) are always higher than the values of *k* in the mine. Additionally, the more different are the grades between the crust and the deposits, the higher is the difference between the values of *k*.

Table 9. Values of *k*, when $x=x_c$ and $x= x_m$, calculated with ERC (1) and ERC (2) for copper, gold and zinc.

	ERC [GJ/t] (1)		**ERC [GJ/t] (2)**	
	k ($x=x_c$)	k ($x=x_m$)	k ($x=x_c$)	k ($x=x_m$)
Copper (chalcopyrite)	525	170	1,222	183
Gold	6,380,357	2,135,879	5,969,213	2,153,212
Zinc (sphalerite)	104	13	652	13

d) Gallium, germanium and indium

Gallium, germanium and indium are critical metals for new technologies, such as mobile phones or solar cells. They have also been listed as critical raw material in the report made by the European Commission (European Commission, 2014) regarding this issue. Therefore it is important to have an approximation of their exergy replacement costs.

The exergy replacement costs of gallium, germanium and indium can be calculated based on the concentration in the mains ores of which they are extracted. In the case of gallium, bauxite is the main ore, and for germanium and indium, they are usually extracted form zinc ores.

Using the information available of the energy use in the extraction of the main ores and knowing the average concentration of these elements in their corresponding ores, exergy replacement costs of each can be calculated (Table 10). As their concentration in the crust and in the mine is quite low when compared to other minerals, it is logical to expect high values of ERC.

Table 10. Average concentration in the crust (x_c) and in the mine ($\underline{x}_m$) and exergy replacement costs (ERC) for gallium, germanium and indium.
(1) Schutle & Foley (2014); (2) Höll, Kling, & Schroll (2007); (3) Alfantazi & Moskalyk (2003).

	x_c **[g/g]**	x_m **[g/g]**	**ERC [GJ/t]**
Gallium (in bauxite)	1.76E^{-05} (1)	5.70E^{-05} (1)	147,235
Germanium (in zinc)	1.41E^{-06} (2)	3.00E^{-03} (2)	24,974
Indium (in zinc)	5.61E^{-08} (3)	4.50E^{-04} (3)	366,591

2.5. MAIN RESULTS AND CONCLUSIONS

In this chapter an analysis of the energy use as a function of the ore grade and as a function of time has been accomplished. The extractive industry is very energy consuming, as between 8 and 10% of the world total energy consumption is devoted to this sector. For this reason having more accurate and reliable information is becoming a crucial issue.

As stated before, numerous studies have focused on the energy consumption of mining projects, carrying out the analysis primarily in one single country or one single element (Mudd, 2007b; Mudd, 2007c; Mudd, 2010b). Nevertheless, the information obtained in this section represents a new and more accurate approach. For the first time, the most important mines that extract economically important minerals from several countries have been selected and included in the energy and ore grade analysis. The information related to energy use and ore grade has been collected directly from the mining companies' reports and databases have been updated with data up to 2014.

After analyzing the energy intensity use as a function of the ore grade in a selection of 40 metallic mineral mines, the main conclusion that can be drawn is that as the ore grade decreases in the mine, the total energy consumption per tonne of ore seems to increase. Additionally, as the ore grade decreases, the diesel and electricity used per tonne of ore mined also seems to have an increasing tendency. Underground mines are more energy consuming than open cut mines, as demonstrated by the *Granny Smith* gold mine (Australia), and the process of each mine also has a big influence in the energy consumption pattern. Still, ore grade seems to be one of the most important factors affecting the total energy consumption in the mining industry.

Additionally, with the case of copper, the evolution of the ore grade, energy consumption and copper produced over time has been examined. The general tendency is that average copper ore grade decreases over time, while the energy consumption and the material produced increases. Observing only Chilean copper mines, the average ore grade has decreased an average of 28.8% in just ten years. In the case of energy consumption in all the copper mines selected for this study, there is a 46% increase from 2003 to 2013, while the increase of copper produced for that same period is 30%. This seems to be in accordance with the historical trends observed for Australian mines and for other mines at global level.

Starting from the data obtained from sustainability and annual reports of several mining companies, data of energy use (in GJ/t) as a function of the ore grade has been compiled for copper, gold and zinc. With this information new values for exergy replacement costs have been recalculated to improve the Physical Geonomics model. Additionally, using the average concentration data of gallium, germanium and indium in bauxite and in zinc, their respective exergy replacement costs have been estimated (Table 11).

Table 11. New values for exergy replacement costs for selected substances.

	x_c **[g/g]**	x_m **[g/g]**	x_r **[g/g]**	**ERC [GJ/t]**
Copper (chalcopyrite)	$6.64E^{-05}$	$1.67E^{-02}$	$8.09E^{-01}$	256.82
Gallium (in bauxite)	$1.76E^{-05}$	$5.70E^{-05}$	$9.99\ E^{-01}$	147,235
Germanium (in zinc)	$1.41E^{-06}$	$3.00E^{-03}$	$9.99\ E^{-01}$	24,974
Gold	$1.28E^{-09}$	$2.24E^{-06}$	$1.38E^{-04}$	546,057
Indium (in zinc)	$5.61E^{-08}$	$4.50E^{-04}$	$9.99\ E^{-01}$	366,591
Zinc (sphalerite)	$9.96E^{-05}$	$6.05E^{-02}$	$7.90E^{-01}$	155.03

When comparing the new exergy replacement costs values based on empirical data with the previous ones obtained only from theoretical data, it can be seen that the ERC of copper and zinc change considerably, increasing 57 and 84% respectively. For the case of gold, as the ERC had already been contrasted with empirical data, therefore adding new empirical data only slightly changes the final value. For the case of gallium, germanium and indium, as the current ERC have been calculated using their respective main ores, they must be only taken as an approximation. Still, the values seem to be consistent as they all are very scarce substances and their concentrations in the crust and in the mine are quite low.

The most important conclusion of this chapter is that decreasing ore grades is no longer a theoretical issue but a global reality caused by the increasing consumption of raw materials as demonstrated by the empirical and updated data presented here. Decreasing ore grades entails increases in the amount of ore mined and energy intensity, enhancing environmental and social costs. As this is not a trivial matter, comprehensive studies should be carried out considering the scarcity of raw materials in the accounting systems.

3. GLOBAL INDICATOR TO EVALUATE RESOURCE EFFICIENCY

The use of indicators to evaluate several factors, in this case resource efficiency, is widely extended as they can provide easy and straightforward information in just one numeraire. As stated in the previous chapter, depletion, energy use and declining ore grades are a reality and developing indicators that can take these issues into account becomes fundamental to properly evaluate our resources and environmental performance.

In this section a quantification of the use and efficiency of natural resources has been carried out using a global indicator proposed by the European Commission (European Commission, 2011), GDP/DMC (Gross Domestic Product as a function of the Domestic Material Consumption). This indicator has been evaluated from a thermodynamic perspective to analyze its suitability. Additionally, a new indicator has been proposed to include the scarcity factor into account.

The main results and conclusions of this subsection are fully developed in the following paper:

- Valero, A., Valero, A., Calvo, G. (2015). **Using thermodynamics to improve the resource efficiency indicator GDP/DMC.** *Resources, Conservation and Recycling*, 94, 110-117.

3.1. METHODOLOGY

Indicators are extremely helpful as they can be used in the decision making process by providing simple, clear and aggregated information for policy makers. Indicators additionally can measure and calibrate progress towards sustainable development and give an overall picture of the situation.

Starting from the input and output information gathered about mineral trade, a series of mineral dependency indicators can be calculated to evaluate the evolution of the mineral dependency and resource efficiency through time.

Domestic material consumption (DMC) can be used to measure the total amount of materials directly used, excluding hidden flows, and is calculated as follows:

$$\text{DMC} = \text{extraction} + \text{imports} - \text{exports}$$

Using the ratio between domestic extraction (DE) and domestic material consumption (DE/DMC), the self-sufficiency ratio can be obtained. With this ratio the current mineral extraction can be compared with the needs of a region and observe if they are met or not. High values of DE/DMC would indicate that the region analyzed is self-sufficient and does not need to rely on imports; lower values would mean a low self-sufficiency, in other words, a high dependency on external supply.

Moreover, with import to DMC (I/DMC) and export to DMC (E/DMC), foreign dependency ratios can be estimated. High values of I/DMC would mean that the region under observation needs to rely on imports to cover its own needs and high values of E/DMC would mean that exports play an important role in the economy.

Additionally, DMC is usually combined with GDP to measure resource productivity, but by using only DMC the dispersion of minerals is not being properly evaluated. This is why the recycled materials should be also taken into account in the calculations, changing the parameter DMC to DMD: domestic material dispersion, which is calculated as follows:

$$\text{DMD} = \text{extraction} + \text{imports} - \text{exports} - \text{recycling}$$

While all the aforementioned indicators are usually measured in tonnes, the dispersion of materials can be additionally assessed through exergy replacement costs to better reflect the quality of the mineral resources that are being evaluated. Not only the consumption of resources is relevant, but also the dispersion. Minerals, with the exception of fossil fuels, are not lost when they are consumed, as in the worst case they end up as wastes in landfills before becoming dispersed. Additionally, when using this indicator only in tonnes, one is adding tonnes of iron with grams of gold, comparing “apples with oranges”. Policies oriented towards a reduction in material use would then give a wrong indication; encouraging decreases in consumption of the most commonly used materials (the ones that are extracted in greater quantities) which are not necessarily the most critical ones. A decrease of those abundant minerals would not lead to a collapse in the economy, but a shortage in critical raw materials could cause it. Therefore, the main goal of using DMD is to provide a global resource efficiency indicator that can present useful information taking into account not only the conventional parameters that are traditionally used but also dispersion. This new indicator could be then used as a decision-making tool for policy use, directly incorporating scarcity information on mineral resources, and it can be used both at local and global scale.

Additionally, using the DMD indicator instead of DMC, if recycling rates increase, more material recirculates in the system and that could lead to reduction in extraction and imports, leading to a decrease in material dispersion. Some metallic minerals are recycled as long as the recycling costs are lower than those of extraction, thereby avoiding the extraction of additional raw materials. This is the case of metallic minerals such as aluminium, copper or lead, as recycling them saves around 95, 85 and 65% respectively of the energy consumption when compared to the primary production (Wellmer & Steinbach, 2011). But many other minerals, such as minor metals that are used in Waste Electrical and Electronic Equipment (WEEE) are currently not recycled as recovery technologies are underdeveloped and they directly end up in landfills.

Thus, DMD, when expressed in exergy replacement costs, can provide a better picture of the situation and be subsequently combined with other parameters, such as GDP, to provide a more accurate assessment of raw material depletion.

3.2. MAIN RESULTS

In order to assess and monitor the environmental performance of a region or nation, indicators can be derived from any material flow analysis to provide a general vision and give us an insight of how an economy interacts with natural resources. Indicators can also be used as a reference point to carry out comparative analysis between different periods or regions. Usually the indicators based on material flow analysis are elaborated using only mass terms as a yardstick, providing information that may be biased or incomplete. For this reason, complementing the analysis using exergy replacement costs is necessary to have a better overall picture of the mineral depletion situation.

In this section a series of resource efficiency indicators have been calculated using the extraction and trade data of a region. In this case, the indicators used, calculated both using tonnes and exergy replacement costs, and are the following:

- DMC: domestic material consumption, defined as extraction plus imports minus exports.
- DMD: domestic material dispersion, defined as extraction plus imports minus exports minus recycling.

The DMC indicator is widely used to evaluate the mineral dependency over time of a region and is usually combined with GDP for comparative purposes. Indeed, the European Commission proposed to use this indicator, DMC/GDP, as the lead indicator to measure resource productivity. As not only consumption or natural resources but also dispersion is relevant, DMC can be changed to DMD, and use exergy replacement costs instead of tonnes to assess additionally mineral dispersion.

Using the Spanish mineral trade for the year 2009, the impact in the indicator of the changes in extraction, imports and recycling of selected substances has been evaluated, stating that DMD is a better choice than DMC to evaluate resource efficiency. In Table 12 we can see for instance that DMC remains invariable when more recycling is undertaken but that DMD changes. Additionally, using exergy replacement costs instead of tonnage can put more emphasis on the quality of the resources. For instance, a 30% increase in limestone production has a higher impact when DMC is expressed in tonnes (19.33) than that same increase in fossil fuel imports (8.72). Nonetheless, when expressed in exergy terms, the weight of limestone decreases (2.07) and the weight of fossil fuels increases (13.42). Logically fossil fuels are scarcer and more valuable than limestone, so using exergy replacement costs instead of tonnes results in a better and more comprehensive approach.

Table 12. Variation in percentage of the studied indicators when the initial variables change. Data are based on extraction, imports and exports in Spain for the year 2009.

	ΔDMC [t]	**ΔDMC [Mtoe]**	**ΔDMD [Mtoe]**
Limestone -20%	-12.88	-1.38	-1.58
Limestone +30%	19.33	2.07	2.37
FF +10%	2.91	4.47	5.12
FF +30%	8.72	13.42	15.35
FF +50%	14.53	22.36	25.58
FF +30% Limestone -30%	28.04	15.49	17.72
FF +30% Limestone -13.5%	0.02	12.49	14.28
Recycling +20%	0	0	-2.88
Recycling +50%	0	0	-7.20

3.3. PAPER I: USING THERMODYNAMICS TO IMPROVE THE RESOURCE EFFICIENCY INDICATOR GDP/DMC.

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Using thermodynamics to improve the resource efficiency indicator GDP/DMC

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ABSTRACT

This paper analyzes the drawbacks of using the lead indicator Gross Domestic Product divided by Domestic Material Consumption (GDP/DMC) proposed by the European Commission as part of the Resource Efficiency Roadmap. As an alternative, we propose to assess mineral resource efficiency through exergy replacement costs instead of using mass terms. Exergy replacement costs represent the useful energy that would be required to return minerals from the most dispersed state (the bedrock) to their original conditions (of composition and concentration in the mineral deposits). Dispersing a scarce mineral such as gold or oil has a much higher replacement cost than that of iron or limestone and in the final accounting, the first minerals have a greater weighting. Consequently, the tonnage produced and dispersion degree are considered in the proposed index. This new index would lead to more developed policies that could reduce the consumption of scarce materials with higher replacement costs. The suitability of the proposed indicator is evaluated through the case study of mineral balance in Spain.

1. Introduction

Using the earth's limited resources in a sustainable manner is the key for resource efficiency. Natural resources such as metals, minerals, fuels, water and land are fundamental for the economy and also for human welfare; they all constitute vital inputs that keep the economy functioning. In the last decades the demand and use of materials has increased exponentially, not only the demand of common materials such as limestone or iron ore, but also the demand for rare and strategic natural resources used in green technologies (Alonso et al., 2012).

A suitable way to evaluate resource efficiency is material flow analysis (MFA), which enhances the understanding of the material basis of the economy and helps to identify inefficient use of natural resources. It is also a good basis to further improve our understanding of the metabolism of economy and society (Bringezu et al., 2003). MFA can provide an integrated view of the physical resource flows through the economy and reveal how these flows of materials shift among and within countries. Depending on the flows we want to analyze, material flow analysis can be centered in certain substances or materials to study specific impacts or consider all the material flows to see the metabolic performance of a region (Bringezu and Moriguchi, 2002).

In order to assess and monitor the environmental performance of national and regional economies, indicators can be derived from any material flow analysis to provide a general vision. They can give us an insight on how an economic system interacts with natural resources and material flows, observing the implications of globalization and trade (Organisation for Economic Co-operation Development, 2008). As several studies have already demonstrated, indicators can also serve to provide a quick comparison between different countries or to evaluate the evolution of a particular region during different periods (Bringezu et al., 2004; Kovanda et al., 2012; Galli et al., 2012; Browne et al., 2011; Raupova et al., 2014).

Over the last decades plenty of indicators have been developed and suggested: Ecological Footprint, Human Development Index or the Happy Planet Index. Other indicators based on energy, land and water use from micro- to macro-level were discussed by Giljum et al. (2011). Each of these indicators provides a different type of information, being complementary rather than competitive.

A series of indicators can be derived from economy-wide material flow accounts, providing information on essential characteristics of the socio-industrial metabolism. They can be grouped into input, output, consumption, balance, productivity and consistency indicators (Bringezu and Schütz, 2010). The most commonly used material consumption indicators are direct domestic material consumption (DMC), total material consumption (TMC), Net Additions to Stock (NAS) and Physical Trade Balance (PTB) (Eurostat, 2001). DMC measures the total amount of materials directly used by an economy and is defined as the annual quantity of raw

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materials extracted from the domestic territory, plus all physical imports minus all physical exports. TMC includes the use of all domestic and foreign primary materials for production and consumption. NAS measures the physical growth of the economy, meaning the quantity of new construction materials used in infrastructures and materials incorporated into new durable goods. PTB measures the physical trade surplus or deficit of an economy, calculated as imports minus exports.

The main problem with most indicators is that they are frequently linked to economic factors. It is important to find tools to measure decoupling of resource use from the economic growth and decoupling of environmental impact from resource use. Currently some efforts are being made in this regard. Van der Voet et al. (2005) proposed the Environmentally weighted Material Consumption (EMC), an indicator that combines information on material flows with information on environmental impacts. Giegrich and Leibich (2008) proposed the Environmental Impact Load (EVIL), which combines different impacts which affect environmental safeguard subjects. EVIL corresponds to the acceptable maximum of environmental impacts which guarantee the sustainable development of society. Since it is based on political conventions, the quantification can be subject to changes according to existing and developing knowledge and value judgments. Recently the Japanese government introduced indicators based on specific solid waste management and material flow analysis, which helped to increase significantly its recycling levels and reduce the amount of final disposal waste (Yabar et al., 2012). These indicators proved to be effective in terms of decoupling economic development from resource consumption, but it is still necessary to link them to other direct environmental and resource indicators.

In this paper we are going to focus on DMC and the derived indicator, GDP/DMC, that was proposed by the European Commission to measure the resource efficiency of a country. We will analyze its suitability and also recommend an alternative indicator, GDP divided by Domestic Material Dispersion.

2. Roadmap to a Resource Efficient Europe

The European Commission (EC) recently developed the Roadmap to a Resource Efficient Europe (COM (2011) 571) (European Commission, 2011). This was carried out in response to unsustainable over-use of environmental resources and increased price volatility, and also in its recognition of the essential role played by both mineral and environmental resources in providing economic stability and growth. Environmental resources include rare earth metals, water, climate, fish, biomass, fertile soils, clean air and ecosystem services. The Resource Efficiency Roadmap (RER) is part of the Resource Efficiency Flagship of the Europe 2020 Strategy. As stated by the EC:

> "The Europe 2020 Strategy is the European Union's growth strategy for the next decade and aims at establishing a smart, sustainable and inclusive economy with high levels of employment, productivity and social cohesion. The Roadmap to a Resource Efficient Europe outlines how we can transform Europe's economy into a sustainable one by 2050. [. . .] It provides clear signals to all economic actors by adopting policy goals to achieve a resource-efficient economy and society by 2020, setting targets that give a clear direction and indicators to measure progress relating to the use of land, material, water and greenhouse gas emissions, as well as biodiversity. Such indicators must go beyond conventional measures of economic activity, help guide the decisions of all actors, and assist public authorities in timely action."

Within this context, the European Commission proposed to use as the lead indicator "Resource Productivity", GDP divided by Domestic Material Consumption in euro/ton. Even if they recognize it has some considerable drawbacks, such as that the indicator is insensitive to changes in the environmental pressures and that the economic value, scarcity and environmental impacts are only partially correlated to the weight of the resources. To compensate its limitations, this lead indicator is intended to be complemented with a dashboard of macro indicators and some specific indicators to measure progress toward the specific objectives and actions.

3. Key issues that need to be addressed by indicators to support resource policy

The indicators used need to address all the issues related to avoiding the identified risks of resource supply and the consequences of resource use in the European Union (EU). This paper mainly focuses on mineral resources, although the same reasoning can be extrapolated to other kinds of resources such as water, land, air.

In June 2010 the Commission published a report on critical raw materials, in which two types of risks were identified (European Commission, 2010):

(a) the "supply risk" taking into account the political–economic stability of the producing countries, the level of concentration of production, the potential for substitution and the recycling rate; and
(b) the "environmental country risk" assessing the risks that measures might be taken by countries with weak environmental performance in order to protect the environment and, in doing so, endanger the supply of raw materials to the EU.

In the report, the concept of criticality was used in the following way: "a raw material is labeled "critical" when the risks of supply shortage and their impacts on the economy are higher than for most of the other raw materials." According to this definition, 14 minerals were considered very critical. Among others, these included rare earths, Platinum Group Minerals (PGMs), germanium, tungsten, indium or niobium, all of which are of paramount importance in the development of renewable energy, informatics and communication technologies (Moss et al., 2013; Habib and Wenzel, 2014; Baldi et al., 2014). Also in 2011, the US Department of Energy published a similar study assessing the criticality of certain substances in wind turbines, PV cells, EVs and fluorescent lighting (United States Department of Energy, 2011). Taking into account the importance for clean energies and supply risk, they identified 16 elements, not exactly the same as the EC, but also equally critical. This indicates that, even if some work related to critical materials is being done, it still needs to improve and find indicators that can supply enough information. Indicators that are not able to address the aforementioned issues will fail, or at best not support, appropriate resource policies.

The EC report considers three main aggregated indicators that address the economic importance of the considered raw material, its supply risk and an environmental country risk assessing the potential for environmental measures that may restrain access to deposits or the supply of raw materials. According to this report, the economic importance of each raw material has been assessed from the perspective of the value-added of the sectors using them as an input, breaking down its main uses in 17 different sectors (construction materials, metals, electronics, food, paper, etc.). The supply risk comprises the assessment of the political–economic stability of the producing countries, the level of concentration of production, the potential to substitute and the recycling rate.

Finally, the environmental country risk indicator should be based on twelve impact indicators: depletion of abiotic resources, land use competition, climate change, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, maritime aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation (summer smog), acidification potential, eutrophication and ionizing radiation.

4. GDP/DMC and alternatives

4.1. Is the lead indicator GDP/DMC appropriate to measure resource efficiency?

According to the EC, "DMC measures the total amount of materials directly used by an economy and is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports":

$$\mathrm{DMC\,(tons)} = \mathrm{extraction} + \mathrm{imports} - \mathrm{exports} \tag{1}$$

The accounting of materials is done through a material flow analysis (MFA). Carrying out this activity is already an important progress toward the search of a more efficient use of natural resources. Currently, there is an important information gap regarding how minerals are produced, consumed and dispersed. The existing information in mineral databases is often scarce, inaccurate and even sometimes distorted. National geological surveys, which historically have compiled such data, have progressively had less financial resources for the accomplishment of this task. Yet it remains absolutely critical that the EU enhances the compilation of data through the RER. A fundamental starting point for the good management of resources is a systematic and rigorous inventory of mineral commodities which is an exhaustive and time consuming process.

Nevertheless, the huge effort required for the data compilation process is done so in vain if the indicators used are not able to give appropriate indications. In this respect, the lead indicator GDP/DMC does not provide enough information in the identification of the aforementioned risks, based on the following:

(1) In focusing in Eq. (1), it is not only the consumption of resources which is relevant but also the dispersion of materials within the EU's borders. In general, minerals, with the exception of fossil fuels, are not lost when they are consumed. In the worst case they end up as wastes in landfills before becoming dispersed. However, some of them are recycled, thus avoiding the extraction or importation of additional raw materials. This obviously will occur as long as recycling costs are lower than those of extraction. This is the case of secondary aluminum, copper or lead production, which saves around 95%, 85% and 65% of the energy consumption respectively compared to primary production (Wellmer and Steinbach, 2011). On the contrary, many minor metals used in Waste Electrical and Electronic Equipment (WEEE) are currently not recycled as recovery technology is largely underdeveloped and the associated costs do not pay off. Moreover, it should be noted that if all materials produced were recycled, extraction would not stop, since consumption historically increases exponentially as shown in Fig. 1. Even if when measuring the total amount in tons of materials directly used by an economy there is no essential difference in taking or not into account the recycled materials, since only a tiny percentage of the materials are recycled (particularly aluminum, copper, iron or zinc), nonetheless it should be included in the equation to reflect the dispersion of the materials. Should this be taken into account, we propose to change the parameter DMC to DMD: Domestic Material Dispersion:

$$\mathrm{DMD} = \mathrm{extraction} + \mathrm{imports} - \mathrm{exports} - \mathrm{recycling} \tag{2}$$

If recycling rates increase and more material recirculates in the system, presumably the term "extraction + imports" could be reduced consequently diminishing the material dispersion.

(2) Such an aggregated indicator does not supply enough relevant information. Besides, in the same index, one is adding tons of iron with grams of gold and this is as if one were to compare "apples with oranges". This also means that should the consumption of iron reduce and the consumption of the scarce metals such as gold or even other critical materials such as cobalt or neodymium (whose orders of magnitude of production are thousands times lower than those of iron or aluminum) are reduced, the obtained index would give a wrong indication. And thus the policies oriented toward the proposed indicator would lead to a reduction in the consumption of the most commonly used minerals worldwide (iron, phosphate rock, gypsum, aluminum, limestone and fossil fuels – Fig. 1), which are not necessarily the most critical ones, as pointed by the European Commission (2010). Economies do not collapse if the consumption of those abundant minerals increase, but could eventually do so if there are shortages in critical raw materials. This fact is explained below through the Spanish case study.

(3) MFA is a good starting point for accounting purposes. However, failing to go beyond that would imply that only facts in the past are taken into account. Ideally, the indicators should also be able to alert about future shortages, penalizing the use of critical minerals.

On this basis, we are going to propose an alternative indicator which should overcome the above deficiencies (or at least some of them).

4.2. The exergy replacement costs as an alternative indicator to GDP/DMC

We propose to assess the dispersion of materials through exergy replacement costs. These represent the energy that would be required to return the minerals from the most dispersed state (the bedrock) to the original conditions (of composition and concentration in the mineral deposits). The same applies for water, land, air, etc. Using exergy replacement costs means that the same units (energy units) can assess any substance (and thus one ceases to compare apples with oranges).

Exergy is a physical property based on the Second Law of Thermodynamics that measures the quality of a system under analysis with respect to a given reference. So any system that differs in its physical properties (be it temperature, pressure, composition or concentration) from the surrounding environment has exergy and as such, has the potential to do work. To use examples: a fluid at high temperature and pressure with respect to the atmospheric conditions has a certain amount of exergy that can be used to produce work through a turbine, for instance. The freshwater from a natural spring in the mountains has exergy because of its height and purity with respect to salty water in the ocean at sea level. In the same way, a mineral deposit has exergy because it has a specific composition and concentration different to that of the average dispersed crust. This saves man huge amounts of energy that would be otherwise wasted if resources were to be extracted directly from the crust. The property exergy has been extensively used for the optimization of thermal processes. However, it is gaining importance as a numeraire for assessing natural resources. Some prominent studies that use exergy for natural resource accounting are those of

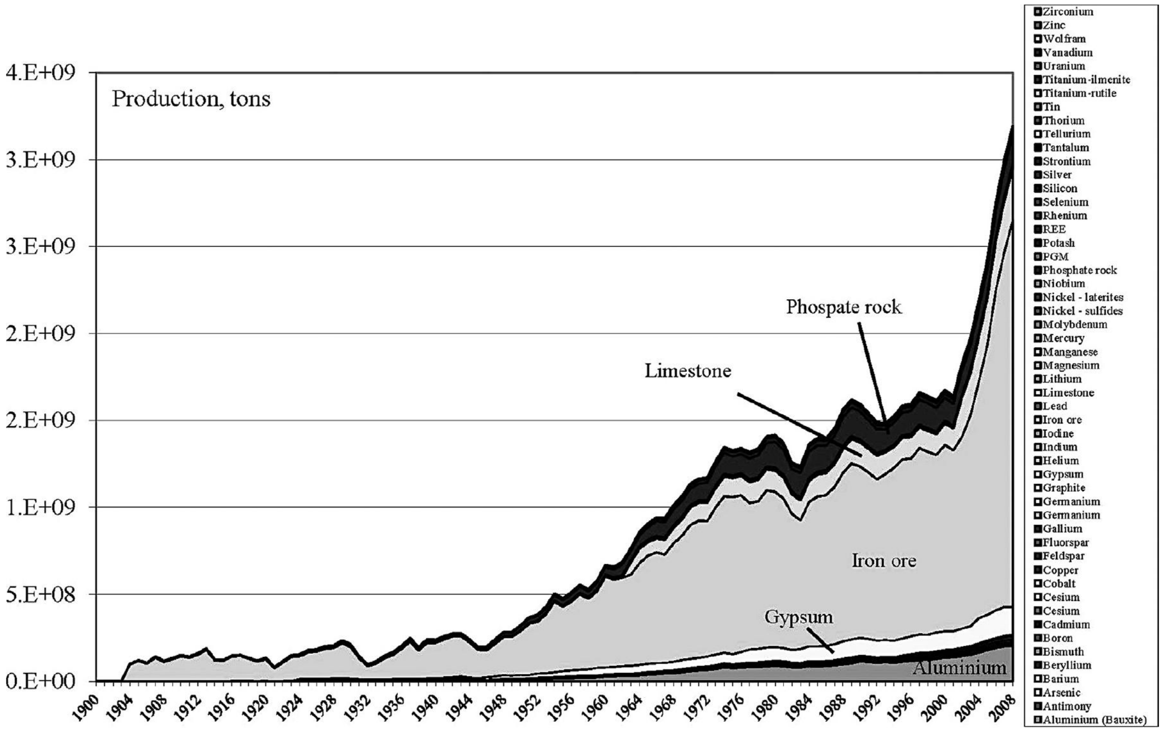

Fig. 1. Evolution of the extraction of minerals in the world throughout the 20th century
Data obtained from USGS (1900–2008).

Finnveden and Ostland (1997), Ayres (1998) or Wall and Gong (2001).

For the quantification of the exergy replacement costs of minerals, a model of average dispersed crust is required. This model of dispersed crust was developed by Valero et al. (2011). Thanatia (in Greek meaning death) was the name given to the resulting planet of that model and describes the possible state of the earth when all commercially exploitable resources have been consumed and dispersed. The greater the difference between concentration of the mineral in the mine and of that in Thanatia, the greater is the exergy content of the deposit. The Thanatia model includes a list of minerals with their respective average concentrations in the crust which constitute the lower limit of ore grades. The exergy of the minerals, calculated from Thanatia, accounts for the minimum energy required to restore the minerals from a degraded state back into the conditions found in Nature.

When materials become degraded and dispersed, they arrive at similar conditions as those in the dispersed state of Thanatia. Consequently, the costs associated with obtaining these raw materials from the minerals dispersed in Thanatia would include the natural processes of concentrating and forming minerals into mineral deposits (replacement costs) and also those of mining and refining the minerals (extraction and processing costs). It is important to make a clear distinction between these terms. The first, the replacement costs, assesses the resource from Thanatia to the mine. The latter, extraction and processing costs, assesses the resource from the mine to the market.

The exergy calculated from Thanatia gives a measure of the quality of the resource and constitutes a universal, objective and useful tool for classifying resources according to their depletion states. This approach allows for a complete Life Cycle Analysis (LCA) by including the grave to cradle stage as depicted in Fig. 2.

Scarcity behaves in a log-normal way and each time materials are dispersed, the exergy needed to recover them from the environment increases exponentially. Therefore, scarce materials have much higher natural concentration exergies than common ones. As a result, gold or cobalt has much higher replacement costs than iron, lime or silicon which are more abundant and in the crust. Consequently, in the final accounting, these minerals with higher replacement costs have a greater weighting. Hence, both factors (tonnage produced and dispersion degree) are considered in the proposed index. Furthermore, the index would lead to enhance policies that reduce the consumption of scarce materials with higher exergy replacement costs.

Exergy replacement costs of a list of minerals, denoted by b^* (GJ/ton) have been calculated on a thermodynamic basis (Table 1). The detailed methodology by which the table was constructed is described in Valero and Valero (2010, 2012a,b). It should be noted that fossil fuels once they are burnt cannot be recovered. Hence, fossil fuels are assessed in terms of their chemical exergy which is taken on average as 39,394 kJ/N m^3 for natural gas, 45,664 GJ/ton for oil, and 22,692 GJ/ton for coal (Valero and Valero, 2010).

Non-exergy practitioners do not need to know the intricacies of the methodology and the calculations required to produce the results shown in Table 1. Taking into account the proposal of using Domestic Material Dispersion instead of Domestic Material Consumption, the DMD for a particular commodity would be calculated as in Eq. (3):

$$(\mathrm{DMD})^{[\mathrm{GJ}]}_{\mathrm{commodity}} = b^*_{\mathrm{commodity}}\,[\mathrm{GJ/ton}] \times (\mathrm{Extraction} + \mathrm{Import} - \mathrm{Export} - \mathrm{Recycling})_{\mathrm{commodity}}\,[\mathrm{ton}] \tag{3}$$

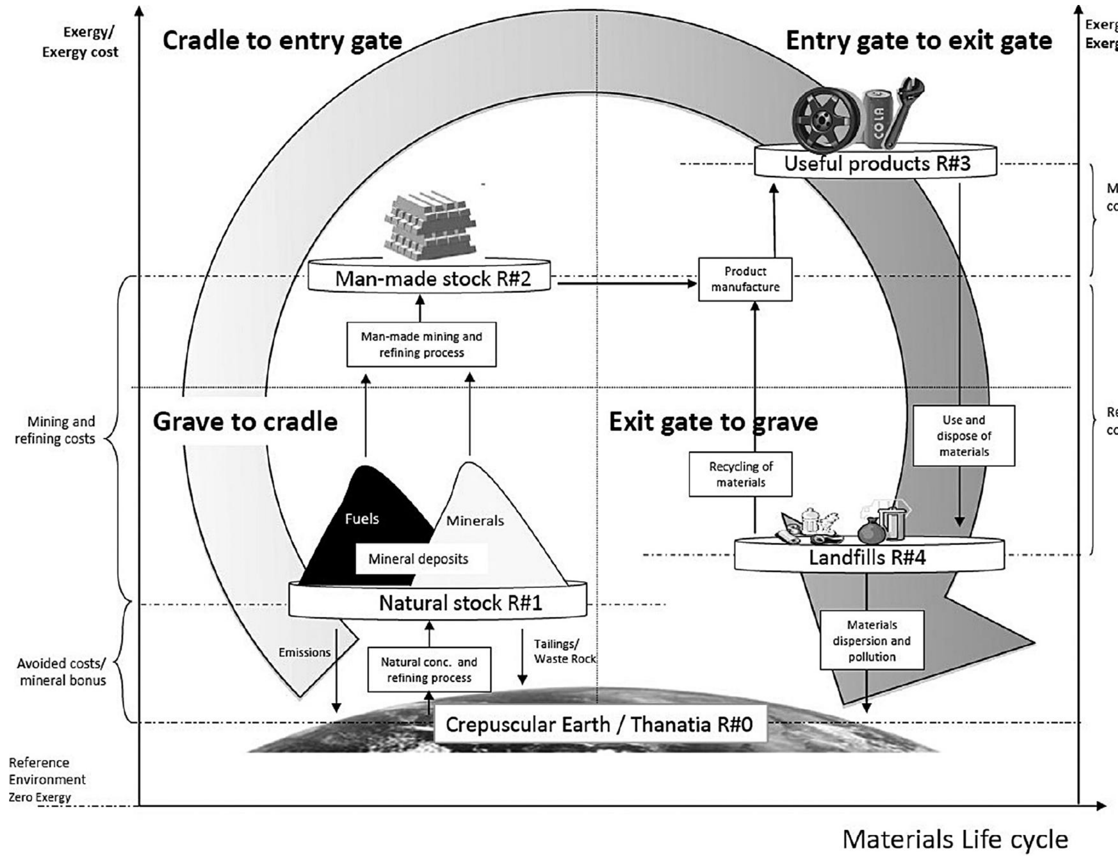

Fig. 2. Life cycle analysis from grave to cradle (Valero and Valero, 2013).

Hence, a material flow analysis is still required, but the latter is complemented with the exergy replacement cost values provided.

5. Case study: application of the proposed indicator to the mineral balance in Spain

The alternative indicator proposed has been used to assess the resource efficiency in Spain for the year 2009. Consequently, information about extraction, imports, exports and recycling rates had to be gathered from different institutions and databases (Geological and Mining Institute, Ministry of Industry, Energy and Tourism of Spain, National Statistics Institute and Chamber of Commerce). Recycling data were especially difficult to obtain and general data for European Union had to be used (United Nations Environmental Programme, 2011). Generally speaking, various datasets and databases for glass, paper and cardboard are available but this is not the case for minerals. This demonstrates the limited concerns about the criticality of minerals, despite their vital importance in the development of societies.

Table 1
Exergy replacement costs (b^*) of selected mineral commodities (Valero and Valero, 2012a).

Material	b^* (GJ/ton)	Material	b^* (GJ/ton)
Aluminum	627	Molybdenum	908
Antimony	474	Nickel (sulfides)	761
Arsenic	400	Nickel (laterites)	167
Beryllium	253	Phosphate rock	0.4
Bismuth	489	Potassium	1224.2
Cadmium	5898	REE	30.8
Chromium	5	Silicon	0.7
Cobalt	10,872	Silver	7371.4
Copper	110	Sodium	44.1
Fluorite	183	Tantalum	482,828
Gold	583,668	Tin	426
Gypsum	15	Titanium (ilmenite)	5
Iron ore	18	Titanium (rutile)	9
Lead	37	Uranium	901
Lime	3	Vanadium	1055
Lithium	546	Wolfram	7429
Manganese	16	Zinc	25
Mercury	28,298	Zirconium	654

The case study mainly focuses on the following substances: oil, coal and natural gas such as aluminum, antimony, bismuth, cadmium, copper, fluorspar, gold, gypsum, iron ore, lead, limestone, manganese, mercury, nickel (produced from sulfides), potash, silicon, tin, titanium (produced from ilmenite), uranium, wolfram and zinc.

Historically, the mining sector has been an important motor of the Spanish economy. The country was leader in the production of mercury and an important producer of zinc, limestone, gypsum and celestine. At the beginning of the 20th century, copper was one of the most extracted minerals along with some other metallic elements such as iron and lead. However, by the end of the 20th century, the Spanish mineral production sector had declined considerably. Many mines closed due to the low ore grade of metallic minerals, mineral depletion or low profitability. Today, only a limited number of mines are still in operation, the majority of which extract industrial minerals. According to the United States Geological Survey, Spain was in 2012 the third producer of gypsum at world

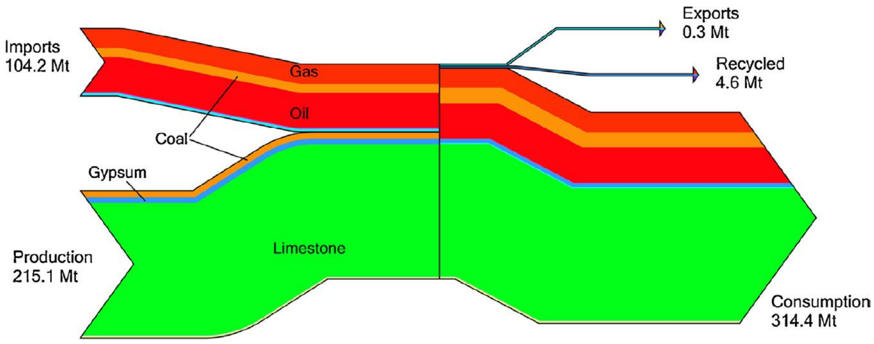

Fig. 3. Spanish mineral balance in 2009 in mass units (Valero et al., 2014).

level and the sixth of fluorspar (Gurmendi, 2012). Still, some studies are promoting the reopening of several wolfram and gold due to the increase of the prices.

As a consequence of the reduced domestic extraction, Spain is a net importer of minerals, especially in the case of fossil fuels, with only a very small fraction of its domestic production exported abroad (Fig. 3). According to the Spanish National Statistical Institute (I.N.E.), the metallurgy and resource sector contributed to 1.8% of the GDP in 2009 (18,384 M€). Fig. 3 shows through a Sankey diagram the 2009 mineral balance in Spain in mass terms.

As can be seen in Fig. 3, if the analysis is carried out in mass units, limestone seems to be the most produced and important commodity in Spain. At the end of the 20th century and the beginning of the 21st, limestone was and remains the most extracted substance of those investigated, with almost 200 millions of tons extracted in 2009, compared to the 8 millions of tons of gypsum extracted that same year. Similarly, fossil fuels are the main minerals imported to the country. Still, the amount of limestone produced is considerably higher than the imports of fossil fuels if we only compare the results in tons.

Fig. 4 shows some of the extraction data for the year 2009 in mass units and also in exergy replacement costs. On this modified basis, limestone acquires a much less prominent position since it is a very abundant mineral and has lower exergy replacement cost than other minerals. Potash becomes more significant, due to the higher replacement costs of potassium (almost 500 times higher than limestone). As explained above, with exergy replacement costs not only is the amount of the commodity produced relevant but also the scarcity degree, calculated as the effort required to replace the considered mineral.

Table 2
Variation in percentage of the three studied indicators when the initial variables change.

	∆DMC (t)	∆DMC (Mtoe)	∆DMD (Mtoe)
Limestone −20%	−12.88	−1.38	−1.58
Limestone +30%	19.33	2.07	2.37
FF +10%	2.91	4.47	5.12
FF +30%	8.72	13.42	15.35
FF +50%	14.53	22.36	25.58
FF +30% Limestone −30%	28.04	15.49	17.72
FF +30% Limestone −13.5%	0.02	12.49	14.28
Recycling +20%	0	0	−2.88
Recycling +50%	0	0	−7.20

In Fig. 5 we can see the percentage of fossil fuel production and extraction, comparing the results obtained in tons and also in exergy replacement costs. As it can be seen, coal is the main fossil fuel produced in Spain but still in 2009 it only covered 43% of the internal needs of fossil fuels, making imports a necessity. Also, in 2009, the degree for oil self-sufficiency in Spain was 0.18% and for natural gas it was 0.04% (Corporación de Reservas Estratégicas de Productos Petrolíferos, 2009).

If the DMC indicator measured in mass terms is used, increasing or decreasing the extraction of limestone would play a determinant role in the efficiency of resource use in Spain. With Spanish data as an example, we analyzed what would happen to those two indicators, DMC and the proposed DMD, in different situations (Table 2).

Even if the consumption of fossil fuels (FF) is increased by 30%, the DMC indicator would show an improvement in resource use (i.e. a negative value of DMC), as long as limestone production is

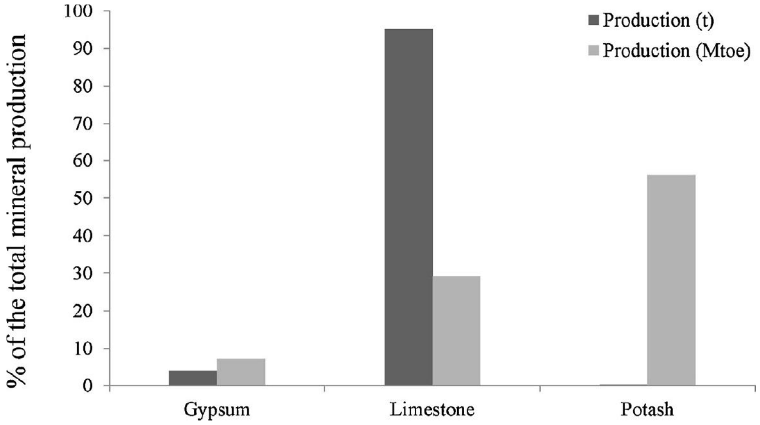

Fig. 4. Comparison between mass units and exergy replacement costs for the domestic extraction of gypsum, limestone and potash in 2009 in Spain.

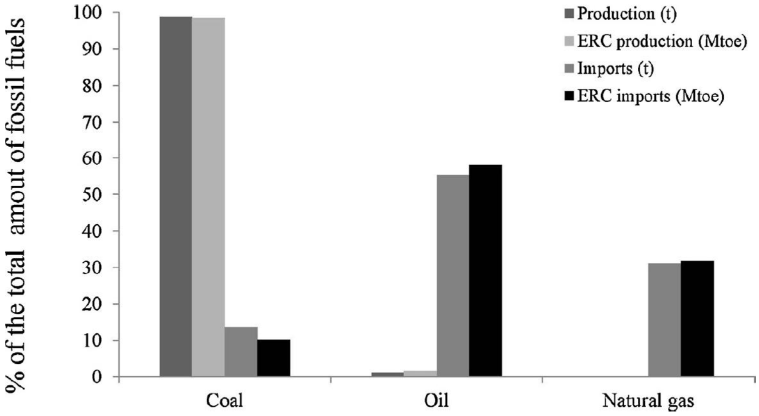

Fig. 5. Comparison between mass units (t) and exergy replacement costs (ERC, Mtoe) for the production and imports of fossil fuels in 2009 in Spain.

reduced by 13.5% or more. However limestone is by no ways a critical mineral, since large amounts of high-grade limestone deposits are located around the globe and its reserves are considered almost inexhaustible. This example is a clear demonstration of the fact that DMC, as initially proposed, is not enough for assessing resource use efficiency.

As shown in Table 2, in Spain's case, the resource use efficiency measured through exergy replacement costs could be effectively improved by reducing the imports of fossil fuels, since scarce materials have a greater weighting. As it can be seen the effect of increasing or decreasing fossil fuels has twice as much impact on the indicator based on exergy replacement costs than on the original one. This indicator gives thus a more valuable information, as it enhances the protection of critical minerals such as fossil fuels and places an emphasis on alternative energy policies and practices.

As stated previously, to complement the indicator, the DMC index should be converted into DMD, since recycling is also an important activity for improving resource use efficiency. Spain is a clear case where resources could be used more efficiently by increasing recycling rates. Today, recycling of metals and industrial minerals only accounts for 2.14% of the minerals consumed in Spain, being aluminum, copper and iron the most recycled materials.

Using the available data from 2009, we have carried out an analysis for several hypothetical scenarios to evaluate the changes if consumption of certain materials increases or decreases; this data can be found in Table 2. This table shows that the DMC index, as opposed to DMD, remains invariable when more recycling is undertaken in Spain. For instance, if recycling rates are increased by 20% or 50%, the DMD improves in 2.88 and 7.20 Mtoe, respectively.

Finally, the index DMD expressed in exergy replacement costs could be subsequently combined with GDP, as proposed by the European Commission in the report, and be converted into GDP/DMD. This way, we would facilitate the usability of the indicator for decision makers. In any case, the conclusions drawn from Table 2 still hold, as for the aforementioned scenarios, the same GDP value is considered.

6. Conclusions

This paper has proved through a case study that resource use efficiency is better described when using exergy replacement costs instead of mass units in the lead indicator proposed by the European Commission (GDP/DMC). We have proposed to include recycling in the analysis, since it is not the consumption of materials which is important, but rather the final dispersion of them. Hence, in the final indicator suggested, DMC, is replaced by DMD as DMD = extraction + imports − exports − recycling (expressed in exergy cost terms).

Yet the proposed index (which could be eventually combined with GDP as in the preliminary EC lead indicator) is not enough. Even if it can be used as an overall indicator, it is important to group certain materials into different categories. The categories used should be related to the different critical aspects identified for resources such as those with economic importance, supply risk (as in the case of rare earth metals) or environmental risk, since exergy replacement costs do not take into account such risks. In this respect, the tier dashboard could be complemented with the indicators described in the aforementioned report of the EC on Critical raw materials for the EU.

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3.4. COMPLEMENTARY RESULTS

In addition to developing indicators that can properly measure resource efficiency, an additional comparative analysis can be carried out using the primary production of fossil fuels along with the main metallic and industrial minerals for the year 2014. Using this primary production expressed both in tones and in exergy replacement costs (ERC), one can put emphasis on the quality of each substance rather that in the quantities.

Figure 26 shows that quantities are not always related with quality. There are some prominent examples, such as the differences between gold, indium, tantalum and tellurium primary production when expressed in tonnes or in ERC. All these metals, that have a major role in technology related products, have higher ERC than other substances, and although the amount of tonnes extracted is lower when compared to other minerals, quality comes into play in ERC. The opposite situation can be observed in the case of barite, phosphate rock or gypsum, more abundant minerals whose primary production values are very high, but when expressed in ERC their importance becomes significantly lower.

As there is going to be increases in future demand of critical metals, such as gallium, germanium, indium, and metals that are in general present in the upper part of the diagram, it can be expected that this upper part could widen on tonnes and especially in ERC terms.

The European Commission has predicted the average increases in demand per year for several critical substances (European Commission, 2014), separating this increase in four categories: very strong (>8%), strong (4.5-8%), moderate (3-4.5%) and modest (<3%). In the “very strong” category we can find niobium, gallium and heavy REE. In the case of gallium this would mean that the primary production would double in ten years, and this would mean in ERC terms, that the production would increase from 1.54 to 3.08, becoming as important as tin or chromium, when compared to 2014 data, in ERC terms.

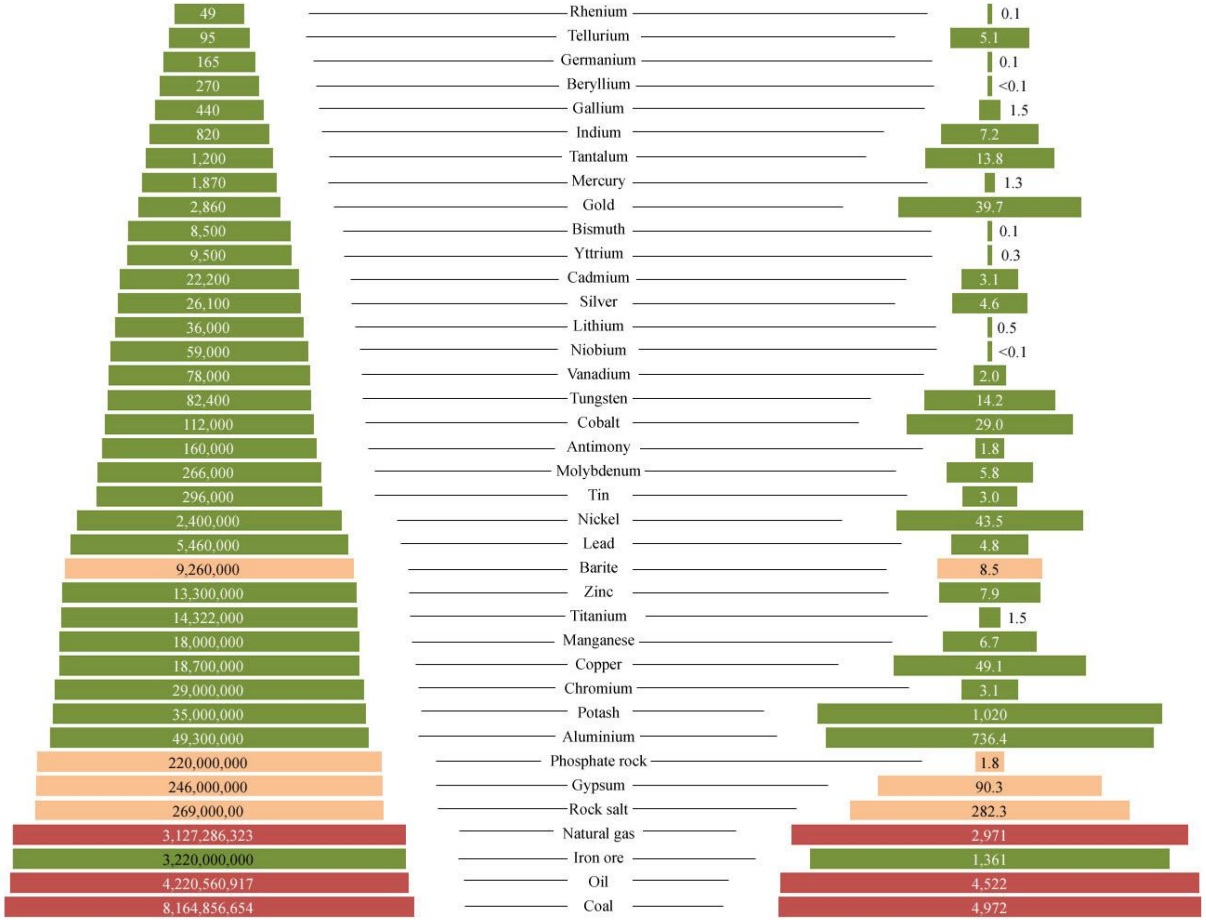

Figure 26. World primary production of selected substances in 2014 expressed in thousand metric tonnes (left) and exergy replacement costs (right) (USGS, 2015a; British Petroleum, 2015).

4. CONVERSION OF EXERGY REPLACEMENT COSTS INTO MONETARY COSTS

The main task developed in this section is the integration of Ecological Economics and Physical Geonomics. For this endeavor, exergy replacement costs have been linked with monetary costs to obtain new values for mineral prices that take into account the replacement of the mineral loss caused by extraction and not only economic factors determined by the market.

The main results and conclusions of this subsection are fully developed in the following paper:

- Valero, A., Carpintero, Ó, Valero, A. Calvo, G. (2014). **How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study**. *Ecological Indicators*, 46, 548-559.

4.1. METHODOLOGY

Exergy replacement costs alone already give enough information on mineral scarcity and depletion. Yet, it can be combined with other factors to obtain more direct and easy to understand information for non-experts, thereby creating a link between Economics and Thermodynamics, which is one of the aims of the Ecological Economics school.

One can easily convert the exergy replacement costs into monetary costs using the current energy prices. This way, one can compare this monetary amount in terms of GDP equivalent and have an approximation of the price associated with the loss of mineral capital. With this information, one can additionally calculate new mineral prices that take into account the mineral depletion and not only extraction and supply demand. This way of performing the calculations is closely related with the "strong sustainability" approach discussed before, as with this analysis natural resources are treated as a complex system rather than being kept constant in monetary terms.

In this case the economic analysis has been carried out only for Spain for the 2000-2012 period.

To convert exergy replacement costs into monetary costs, for the case of fossil fuels the market prices for the years under consideration for each one of them can be used. Natural gas, oil and coal prices have been obtained from *British Petroleum* historical statistical reviews of world energy (British Petroleum, 2015). In the case of non-fuel minerals, as exergy replacement cost represents the amount of energy required to restore the mineral capital extracted with current technology, a range of values has to be used. The lower boundary of the range is calculated assuming that the energy required to replace the minerals comes from coal consumption. The upper boundary considers that this same activity is carried out with electricity, using the average electricity price, obtained from the national statistics services

Table 13. Fossil fuel and electricity prices considered for the 2000-2012 period.
(1) Coal: Northwest Europe Marker price (US$ per tonne). (2) Oil (US$ per barrel). (3) Natural gas: UK Heren NBP Index (US$ per million Btu). (4) Source: Red Eléctrica de España. (5) Source: Banco de España.

YEAR	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Coal (1)	35.99	39.03	31.65	43.6	72.08	60.54	64.11
Oil (2)	28.5	24.44	25.02	28.83	38.27	54.52	65.14
Natural gas (3)	2.71	3.17	2.37	3.33	4.46	7.38	7.87
Electricity (€/MWh)(4)	39	38.4	45.6	37.26	35.65	62.42	65.81
Change €/$ (5)	0.924	0.896	0.944	1.131	1.234	1.247	1.256
YEAR	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	
Coal (1)	88.79	147.67	70.66	92.5	121.54	92.5	
Oil (2)	72.39	97.26	61.67	79.5	111.26	111.67	
Natural gas (3)	6.01	10.79	4.85	6.56	9.04	9.46	
Electricity (€/MWh)(4)	47.38	69.61	42.63	45.36	60.15	59.42	
Change €/$ (5)	1.371	1.471	1.395	1.327	1.392	1.286	

These two boundaries, which can be compared to the GDP and other macro-magnitudes of the country, can give us an estimation of the impact that the depletion of mineral resources would have on the economy. All the fossil fuels and electricity prices used for the Spanish mineral trade analysis are included in Table 13.

Besides calculating the monetary costs associated to mineral trade and dispersion, theoretical mineral prices have been estimated considering that exergy replacement costs are included in the market price accounting system. This analysis has been carried out using the prices of the selected substances expressed in $/t for the year 2009 (Kelly & Matos, 2014).

The actual market mineral prices incorporate, among other things, the energy extraction costs, supply-demand balance, scarcity or stocks and rate of use. Using the relationship between extraction and replacement costs for every mineral, a theoretical mineral price has been estimated (*Price (2)*) considering that the corresponding exergy replacement costs are taken into account in the final price of each commodity (Equation 8). To accomplish this task the assumption that the proportions of other components incorporated in the resource price (labor costs, financial costs, rate of profit, etc.,) remain constant over time has been made.

$$Price\ (2) = Price\ (1) \cdot \frac{RC}{EC} \qquad \text{(Eq. 8)}$$

Being Price (1) the unit value of each mineral expressed in $/t, *EC (extraction cost)* the mining and concentration energy plus refining energy, and *RC (replacement cost)* being *EC* plus the corresponding exergy replacement costs of each substance.

4.2. MAIN RESULTS

Using current energy prices and exergy replacement costs, new mineral prices have been calculated including the price associated with the loss of mineral capital. Selected results are summarized in in Table 14.

When comparing the new mineral prices with the current market prices for the year under consideration (2009), it can be stated that some are 10 to 80 times higher (such are the cases of aluminium, cadmium, cobalt, gypsum, mercury), while for other minerals (such as silicon, titanium, phosphate rock or zinc) the prices remain within the same range in both cases. In general, the new mineral prices calculated are an average of 27 times higher than the current market prices for the year 2009.

Table 14. Selected values for mineral prices for the year 2009.
Price 1 represents the current value of mineral prices for the year under consideration. Price 2 is the new price calculated taking into account exergy replacement costs.

Minerals	**Price 1 [$/t]**	**Price 2 [$/t]**
Aluminium	1,750	33,648
Chromium	2,030	2,283
Copper	5,320	17,002
Iron ore	94	211

Minerals	**Price 1 [$/t]**	**Price 2 [$/t]**
Manganese	1,370	1,742
Nickel	14,600	110,802
Tin	14,100	240,119
Zinc	1,720	2,738

4.3. PAPER II: HOW TO ACCOUNT FOR MINERAL DEPLETION. THE EXERGY AND ECONOMIC MINERAL BALANCE OF SPAIN AS A CASE STUDY.

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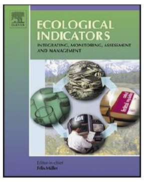

How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study

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Mineral resource accounting

ABSTRACT

This paper describes a way to account for mineral depletion through exergy replacement costs, which are defined as the exergy required to replace minerals from a complete dispersed state back to the initial conditions of composition and concentration in which they were originally found and with the best available technologies. The advantage of using such an indicator is that the scarcity factor of each commodity together with the state of technology can be taken into account. Moreover, as exergy is fully additive, all kinds of resources can be compared. Conducting an exergy analysis of the production for 22 non-fuel minerals in Spain for the year 2009, we obtain that the exergy replacement costs are 41.67 Mtoe, this amount is equivalent to the average domestic coal consumption in Spain for 2 years. If we account for the imports and exports of the 22 substances and we calculate the material consumption, production plus imports minus exports, we have that the total exergy replacement cost increases to 98.97 Mtoe. In the case of fossil fuels, if we add the imports to the Spanish production, the total exergy replacement costs are 94.15 Mtoe, where 93% corresponds only to imports. Depending if the energy source chosen for replacing the domestic mineral capital is in form of coal or electricity, the monetary equivalent of mineral depletion by extraction would be 3272 to 13,518 M€ (between 0.31 and 1.28% of Spanish GDP). If we take into account the total mineral consumption (also including the net flows from the rest of the world), the monetary equivalent would be between 27,408 and 57,008 M€ (2.61 to 5.43% of GDP). We also propose another relevant estimation. If we account for the exergy replacement costs using a *theoretical* price estimated by applying the relationship between extraction/replacement costs to actual price, the monetary value of exergy replacement cost of extracted minerals would be 188,863 M€, 18.62% of Spanish GDP and 84 times higher than the value obtained with current resource prices (2323 M€). For the resource consumption, the monetary value would be 280,594 M€, which represents an equivalent of 26.77% of Spanish GDP and is 25 times higher than the value estimated with actual and current resource prices (11,137 M€).

1. Introduction

Consumption of natural stock is a key element in global society, being economically, socially and culturally dependent especially on minerals. There has been an exponential increasing trend of resource consumption in the last century. Some studies show that the global total material extraction increased over the 1900–2005 period by a factor of 8, the strongest increase corresponding to construction minerals and ores (Krausmann et al., 2009; UNEP, 2011).

Depletion of natural resources is a very important issue that humankind is facing nowadays. With fossil fuels this aspect has been extensively studied but the investigation of the loss of the mineral stock has been neglected until recently and it can be even more crucial for society development. Even if the whole continental crust is composed of rocks as solid solutions, it is inaccurate to say that the minerals are all recoverable and to consider them as an inexhaustible source. The Earth is not and cannot be considered as an infinite reservoir of minerals.

During millions of years, Nature has formed the mineral deposits concentrating the elements through a large number of geological processes. These deposits serve now as a material source for society and the extraction of them implies a reduction of the natural stock. Due to intensive extraction and declining ore grades, mines now tend to be excavated deeper and deeper into the crust and more

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commercially worthless material needs to be removed to obtain the same amount of ore than before. In just one century, humankind has depleted 26% of its world non-fuel mineral reserves, being mercury, silver, gold, tin and arsenic the most depleted commodities (Valero and Valero, 2010). Huge amounts of energy are required to extract minerals as it happens with fossil fuels. Additionally, the mining industry is very water dependent and needs large quantities: for example, to produce a tonne of gold, over 250 Ml of water are required (Norgate and Lovel, 2004).

How to account for this mineral exhaustion and depletion in economic terms has been a controversial issue during several decades. In the next section, we review the debates about how to integrate natural resource accounting at macroeconomic level in the Systems of National Accounts (SNA) and its relationship with the controversy on different views of sustainability. At the same time, we introduce an alternative method (the exergoecology approach), based on thermodynamic grounds, to estimate the loss of mineral resources due to extraction and consumption for economic purposes. This framework allows us to link physical and monetary information more robustly and helps quantifying and clarifying the general objective of sustainability.

2. Beyond monetary mineral resource accounting: the exergoecology approach and ecological economics

Economists concern about how the role of natural resources should be accounted for has a long history. Regarding non-renewable resources, Harold Hotelling's (1931) seminal contribution can be considered the beginning of natural resources (neoclasical) economics. As is well known, Hotelling proposed a rule for optimal extraction of an exhaustible resource ensuring profit maximization in a market under perfect competition conditions. In these circumstances, the price should depend on the marginal revenue and the evolution of the interest rate. The unrealistic character of assumptions behind this approach and the difficulty in operationalizing this proposal leave it basically as a theoretical suggestion.

Some decades later, at the end of 1980s, the debate about depletion of natural resources strongly emerged at macro level in relation to ecological flaws of Systems of National Accounts (SNA) and the possibilities of an ecological adjust of macro magnitudes (e.g. El Serafy, 1989, 2013; United Nations, 2003). Indeed the most widely accepted measure of a country's economic progress is gross domestic product (GDP) since it measures the value of economy's aggregate output of final goods and services in a given period of time. But the main problem is that the current calculation does not take into account many important activities such as the degradation of natural resources or mineral depletion, and sometimes it even encourages depletion of natural resources faster that they can renew (Daly, 1990; Lawn, 2006; Costanza et al., 2009; van den Bergh, 2010). The rise of sustainable development concept and its emphasis on "meets the needs of the present without compromising the ability of future generations to meet their own needs" led to a concern about how to maintain this capacity (i.e., stock of total capital) for producing goods and services and meet the population material needs. Given that total capital stock is the sum of human-made capital (reproducible) plus natural resources or "natural capital" (mostly non-reproducible), the rule of thumb to meet the sustainable development strategy should be maintained the stock of total capital *constant* over time. There is a debate whether the total capital stock should be kept constant in *monetary* terms (weak sustainability) or in *physical* terms (strong sustainability) (see Neumayer, 2010, for an overview). If we accept the weak sustainability approach, one key assumption behind this proposal is to accept a degree of substitutability between human-made capital and natural resources (this means that natural resources may decline as long as human-made capital is increased[1]). From a conventional point of view, if we are interested in maintaining the production capacity of goods and services to meet the population needs (sustainable development), then the economic system should meet the so-called Hartwick's rule: "Invest all profits or rents from exhaustible resources in reproducible capital such as machines. This injunction seems to solve the ethical problem of the current generation short-changing future generations by 'over consuming' the current product, partly ascribable to current use of exhaustible resources" (Hartwick, 1997, p. 972). So we could get a "sustainable income", in a Hicksian sense, that is, the maximum amount that can be spent in consumption without adversely affecting the stock of total capital. From a strong sustainability perspective things are more problematic due to non-substitutable but complementary relation between human-made capital and natural resources. This implies maintaining constant both types of capital in their very physical units of measurement. Some studies have already been made on resource accounting and sustainable development for several countries (e.g. Repetto et al., 1989; Winter-Nelson, 1995; Santos and Zaratan, 1997; Afsen and Greaker, 2007; Prior et al., 2012; Kovanda and Hak, 2011).

In any case, literature on natural resource accounting at national level usually takes a weak sustainability perspective and distinguishes between two general methods to account for the depletion of natural resources into SNA. On the one hand, the loss of natural capital can be treated in a similar way as depreciation of other types of physical capital. Thus, just as Net Domestic Product (NDP) is obtained by deducting from GDP the depreciation value of human-made capital; so environmental adjusting GDP is obtained by subtracting from NDP the depreciation value of natural resources. This procedure is based on the principle that the loss in the value of the mineral reserve between two periods should be subtracted from the national production accounts. Based on this idea, the Net Price Method calculates the value of the resource stock (asset) taking into account the total Hotelling rents attributable to extraction of the resource in a given period of time. Given the assumptions of perfect competition, it implies to maximise the present value of expected future rents (Price–Marginal costs), which multiplied by the resource quantity extracted is considered the depreciation of the natural resource (asset) and should be deducted from NDP (see, for instance, Repetto et al., 1989; Hartwick and Hageman, 1993).

In spite of this proposal, Salah El Serafy showed that the depreciation method is problematic when applied to countries with abundant deposits of mineral resources. As he noted at the end of the eighties: "If we deduct from the gross receipts from mineral sales in any one year an amount equal to the depletion (. . .) the value of *net income* from this activity becomes zero. Where a country derives 100 per cent of its receipts from, say, petroleum extraction – an extreme case of a Saudi Arabia – the depreciation approach (ignoring the multiplier effect of ancillary activities related to extraction as well as the contribution of other sectors to value added) would give us a GDP of 100 and an NDP (Net Domestic Product) of zero—a measurement that is not particularly edifying" (El Serafy, 1989, p. 13).

This result leads us to other general method to adjust national accounts: the so-called user's cost method proposed by El Serafy

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[1] As Eric Neumayer points out: "Loosely speaking, according to WS [weak sustainability], it does not matter whether the current generation uses up non-renewable resources or dumps CO_2 in the atmosphere as long as enough machineries, roads and ports as well as schools and universities are built in compensation.῎(Neumayer, 2010, p. 1). On the contrary, from the strong sustainability perspective, human-made and "natural capitaläre considered non-substitutable but complementary.

(1989). This author suggests that mineral deposits and other natural resources are assets and, by their very nature, their selling does not create value added. This circumstance should be enough not to include the revenue obtained from the sale in GDP. However, given the sale generates a monetary stream, which can be consumed or, in part, invested in alternative uses, we can obtained a perpetual "true income" from this investment that it would be part of GDP and we can enjoy it after the resource is wasted up. The distinction between the "true income" and the total receipts (net of extraction cost) from the sale of mineral resource is a fundamental point in this scheme. It allows differentiating what part of total receipts should be considered as a "true income" and, on the contrary, what part should be treated as loss of "natural capital" and excluded from GDP. The difference between the true income and total receipts from resource sale is the so-called user's cost or factor depletion (El Serafy, 1989, 2013). It should be noted that, both methods allows us to get different incomes associated to extraction of exhaustible resources.

There are, however, several shortcomings when applying these methods. For instance, Net Price Method assumes perfect competition (which almost never met), and that resource rent, meaning the difference between total revenue generated from the extraction of natural resources and all costs incurred during the extraction, will rise at a rate equal to the discount rate of the future (which also never met under the imperfect competition prevailing in the natural resources markets). On the other hand, in order to calculate the user's cost, El Serafy's method uses the net price as a starting point (with the aforementioned problems). It also assumes a constant discount rate (chosen by the analyst), a constant rate of extraction until resource is exhausted, and for that very reason, a constant level of receipts during the assumed lifetime of resources.

If we want to avoid some of the problems related to monetary valuation and weak sustainability perspective, we have to make an effort to link the physical and monetary dimensions on more solid foundations. In this regard, ecological economics provides better prospects. Not in vain, right from the beginning this approach built bridges between economics and natural sciences (e.g. thermodynamics)[2] devoted to study the characteristics and behaviour of energy and materials. Indeed, there are already several ecological economists contributions that analyse the relationship between economics and thermodynamics particularly with regard to the physical aspects of the production process of goods and services and its analytical representation (e.g. Georgescu-Roegen, 1971; Faber et al., 1987; Naredo and Valero, 1999; Faber and Proops, 1996; Baumgärtner, 2004; Baumgärtner et al., 2006; Ruth, 1993; Ayres et al., 2003; Ayres and Warr, 2009).

Besides these aspects, thermodynamics, and in particular the second law, can also be helpful in assessing the deterioration and depletion of different mineral resources used up by an economy. 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). Since exergy is measured in universal units (energy units) and is an additive property within resource accounting, it can be used as a global natural capital indicator, allowing not only the comparison among minerals, but also among other types of resources. This is why an increasing number of scientists (Szargut, 2005; Brodianski, 2005; Wall, 1977; Sciubba, 2003 or Kharrazi et al., 2014) believe that exergy provides useful information within resource accounting and can adequately address certain environmental concerns (Valero et al., 2010).

Using exergy, we can establish a physical similarity between depletion of natural resources at national level with procedures of depreciation allowances applied for the exhausted stock of human-made capital (machines, etc.,), that is, the sum of money which is deducted from business income each year so that funds are available to replace this stock when it is worn out. From a balance sheet accounting framework, robust indicators and measures can be proposed to estimate the physical cost of replacing the natural stock of the exhausted resources. For instance, it would be possible to account for the amount of exergy necessary to replace, in physical terms, the mineral resources stock over time (such as suggests the notion of sustainable development). So, it could be defined as the replacement cost of the mineral resources stock. This way it could be overcome a limitation that appears when we want to estimate the price of a resource and to evaluate its depletion in monetary terms.

Indeed, the price of a natural resource incorporates (among other things) the energy *extraction* costs, but not the *replacement* cost (which would be the case of any other human-made asset considered). However, given the economic power issues in energy and mineral resources markets, and the fact that only living population is allowed to participate in these markets, prices are not a good indicator of future scarcity, and extraction costs are presumably also underestimated. In order to avoid these limitations, mineral depletion should be accounted for considering the *replacement* cost of these resources measured *in physical terms*, not only in monetary terms. Built upon the insights of the second law of thermodynamics, we propose the exercoecology method, initially proposed by Valero (1998), which derives from a general theory developed some years before (Valero et al., 1986), and consists on the application of the exergy analysis to the evaluation of natural resources defined from a reference environment.

Resources are extracted and when the materials are dispersed, the energy used is lost since extraction implies destruction of organized systems; this can trigger an increase in environmental impact. Resource substitution or recycling can be valid in short term to avoid scarcity, but present recycling rates and substituting material technologies are not enough developed and supply for future generations remains at stake.

If this intensive extraction continues and no serious measures are taken, the Earth will be gradually transformed into a depleted one, an Earth where all resources have been consumed and are dispersed, as a direct consequence of the second law of thermodynamics. Even if materials do not disappear, they get eventually dispersed, losing their original quality. In previous papers, a model of the dead planet, called "Thanatia", has been described (Valero et al., 2011). This model of a crepuscular earth represents a degraded planet where all mines have been depleted, materials have been dispersed and all fossil fuels have been burned and converted into CO_2. This model of degraded planet is crucial since it allows us to assess the natural capital and the velocity at which we are degrading the resources. Thanatia's crust can be assimilated to the average mineralogical composition of the current crust.

Exergy takes into account all physical manifestations that differentiate the system from its surrounding, a specific composition and a distribution which places minerals in a specific concentration. It can give us objective information, independently of the economic value of the resources and price speculation. The exergy of a mineral resource is evaluated from its mineralogical composition, ore grade and quantity; it is additive across different minerals and an ideal indicator to assess mineral resource sustainability. With exergy we

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[2] Indeed, from its very beginning in the early 1980's, this approach was institutionalized as a meeting place for two types of transdisciplinary scientists who were dissatisfied with their respective disciplines. On the one hand were economists dissatisfied with how mainstream economics (environmental economics included) represented production and consumption processes without consideration of thermodynamics and ecology. On the other hand, ecologists and physicists were unhappy with the way their respective disciplines left human and socio-economic dimensions aside (Carpintero, 2013; Røpke, 2004, 2005).

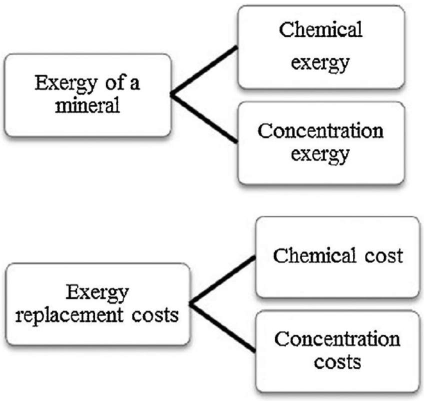

Fig. 1. Components of mineral exergy and exergy replacement costs.

can measure the loss of the free bonus that nature gives us by concentrating the minerals in mines. It allows us to value these resources according to their physical costs, meaning the minimum quantity of useful energy that would be needed to obtain those minerals from a hypothetical Earth that has reached maximum state of degradation. Thanatia serves as a boundary limit and as reference environment for calculating the exergy costs of the commodities.

The main goal of this paper is to establish a model for mineral depletion accounting and see which commodities are those that most affect the mineral balance. We are going to use the exergoecology approach for mineral depletion in Spain, taking into account not only quantity but also quality and scarcity of the resources.

3. Methodology and data sources

The exergy of a mineral deposit is defined as the minimum energy required to restore the mineral deposit from a degraded state into the conditions found in nature. The exergy of a mineral has at least two components, one associated to its chemical composition (b_{ch}) and one associated to its concentration (b_c) (Fig. 1).

The chemical composition has a direct influence of the energy required to process the mineral, and it can be calculated with the following expression (1):

$$b_{ch} = \sum v_k b^0 ch, k + \Delta G_{\min} \tag{1}$$

where $b^0_{ch,k}$ is the standard chemical exergy of the elements that compose the mineral, v_k is the number of moles of element k in the mineral and $\Delta G_{\min}$ is the Gibbs free energy of the mineral.

The concentration exergy is the minimum amount of energy involved in separating the resource from the mineral, and is given by the following Eq. (2):

$$b_c = -RT_0 \left[\ln x_i + \frac{(1-x_i)}{x_i} \ln(1-x_i) \right] \tag{2}$$

where x_i is the concentration of substance i, R is the gas constant (8.314 J/mol K) and T_0 is the reference temperature (298.15 K). This formula is only valid for ideal mixtures and when there is no chemical cohesion among the substances it is also valid for solid mixtures. The calculation of the concentration exergy implies the knowledge of the average ore grade in the mine, x_m, as well as the average concentration in the Earth's crust in Thanatia, x_c. The difference between those two concentration exergies represents the minimum exergy that nature had to spend to bring the minerals from the concentration in the reference environment to the concentration in the mine.

Hence, the total exergy is the sum of the aforementioned components, chemical composition and concentration exergy:

$$b_t = b_{ch} + b_c \tag{3}$$

The exergy replacement costs of the resource, b_t^*, represents the actual exergy that would be needed to recover the deposit from Thanatia with the best available technology. It has also two contributions, the chemical costs, accounting for the chemical production process of the substance, and the concentration cost, accounting for the concentration process.

$$b_j^* = k_{ch} b_{ch} + k_c b_c = b^*_{ch} + b^*_c \tag{4}$$

The dimensionless variable k represents the unit exergy cost of a mineral and is defined as the relationship between the energy invested in the real obtaining process, for mining and concentrating the mineral, and the minimum energy required if the process from the ore to the final product was reversible. Therefore k is a measure of the irreversibility of man-made processes and amplifies minimum exergy by a factor of ten to several thousand times, dependent on the commodity analysed.

The chemical exergy cost of the resource, b^*_{ch}, is used when the reference environment chosen does not contain the substance under consideration. Since Thanatia already contains most of the minerals found in the crust, the chemical exergy is not needed, except in the case of fossil fuels. For the latter, since they cannot be replaced once they are burned, only its chemical exergy is considered and it can be approximated to their high heating values (Valero and Valero, 2012a).

To carry out the economic analysis, the exergy costs are converted into monetary costs through current energy prices. In the case of fossil fuels we can directly use the market prices for the years under consideration for each one of them (coal, oil and natural gas). In the case of non-fuel minerals, since exergy replacement cost represents the amount of energy required to restore the mineral capital extracted with current technology, we are going to estimate two price boundaries. The lower bound is calculated assuming that the energy required to replace the minerals comes from coal consumption. The upper bound considers that this same activity is carried out with electricity, using the average electricity price for the selected year and for the selected country. These two boundaries, which can be now compared to the GDP and other macro-magnitudes of the country, can give us an estimation of the impact that the depletion of mineral resources would have on the economy.

To assess the mineral depletion of Spain an intensive search in multiple databases has been made. Information has been gathered from different institutions, such as I.G.M.E. (Instituto Geológico y Minero de España), the Ministry of Industry, Energy and Tourism of Spain, U.S.G.S. (United States Geological Survey), I.E.A. (International Energy Agency), I.N.E. (Instituto Nacional de Estadística) and the Chamber of Commerce. It is surprising the lack of data on this subject, both information on extraction and existing mineral reserves is not always up to date, also the lack of in-depth studies on this matter makes it really difficult to obtain accurate data. Since 1856 and to this day, there is an annual report on mining statistics (Estadística Minera) that collects general extraction data, even if the data of some years are very incomplete and have mistakes, they can give us an idea on the extraction quantities, history, opening and closing of the most important Spanish mines. We have compiled the extraction data from the 1900–2010 period from these statistics (Estadística Minera de España, 1900–2010). For the recycling rates data, due to lack of better and more specific data, we have assumed that those reflected by the United Nations Environment Programme for 2011 can be extrapolated to the Spanish mineral balance for 2009 (UNEP, 2012).

4. Case study: Spain

Even if the Romans where already extracting gold in “Las Médulas” (León) during the first century B.C., contemporary mining started in Spain around 1820, where there was a progressive liberalization of mining and when the first mining boom took place in “Sierra de Gádor” (Almería) (Pérez de Perceval Verde and López-Morell, 2013). The mining activity of the XIX century was dominated by small companies, mostly constituted by national capital. It was not until the last decades that the big companies started their activity. During that period, mostly metal extracting mines were opened, such as the ones of the Río Tinto zone (Huelva).

At the beginning of the 20th century, mainly metallic minerals were extracted in the Spanish territory, such as copper, iron and lead. However, there has been a change in the tendency of the mining sector in the second half of the century, and the extraction of industrial minerals (construction materials) related to the emergence of housing bubbles made up the bulk of the total production (Carpintero, 2005). Throughout the years, many mines have closed due to the decreasing ore grade of metallic minerals, mineral depletion and low profitability. With globalization, it became cheaper and easier to simply import the minerals that were needed or directly the by-products.

Nowadays, only a limited number of mines are still in operation, being dedicated most of them to the extraction of industrial minerals such as limestone, gypsum and celestite. According to United States Geological Survey (USGS), Spain was in 2012 the third producer of gypsum at world level, after China and Iran, and the sixth of fluorspar along with Japan and Thailand (USGS, 2012).

With the recent price increase of some metallic minerals, such as gold or wolfram, there are some companies promoting the reopening of certain mines in the northern sector of the country.

Since we rely on previous data of unit exergy costs, concentrating, smelting and refining exergies obtained in previous researches (Valero and Valero, 2012b) we can only analyse approximately half of the mineral production in Spain. Therefore this work is only going to focus on the following 22 substances: aluminium, antimony, bismuth, cadmium, copper, fluorspar, gold, gypsum, iron ore, lead, limestone, manganese, mercury, nickel (from sulfides), potash, silicon, silver, tin, titanium (from ilmenite), uranium, wolfram and zinc. For simplification purposes, it has been assumed that each substance is extracted only from one mineral ore. For fossil fuels, we are going to use the statistics of natural gas, oil and coal (anthracite, bituminous coal, subbituminous coal and lignite). Even if this methodology has some limitations, we also have to take into account that the most important minerals for developing societies are included in this study.

With the concentration exergy, the minimum amount of exergy involved in separating the resource from the mineral, and the average ore grade in the mines and in the Earth’s crust, we can calculate the difference between both states and obtain the minimum exergy that nature had to spend to bring the minerals from the concentration in the reference state to the one in the mine. Taking into account the unit exergy costs for each mineral, we can obtain the exergy replacement costs (Annexes, Table A.1).

As we stated before, for non-fuel minerals we are only going to need the concentration exergy since chemical exergy is used only when the reference environment chosen does not contain the substance under consideration and Thanatia contains already most of the minerals found in the crust. Since fossil fuels cannot be replaced once they are burned, in this case only chemical exergy will be considered.

Once we have the exergy replacement costs, we can convert them into monetary costs taking into account the current energy prices. This way, we can compare this monetary amount in terms of GDP equivalent.

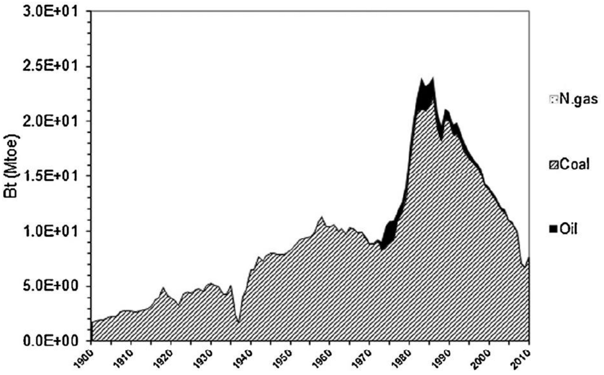

Fig. 2. Fossil fuel consumption in Spain throughout the 20th century.

4.1. Fossil fuels

Fossil fuels represent the remains of plants or animals that gathered their energy from the sun millions of years ago and constitute reservoirs of chemical exergy. Coal is Spain’s main indigenous source of energy, according to the BP Statistical Energy Survey (2012), Spain has 530 million tonnes of reserves, equivalent to 0.06% of the world. Regarding to oil and natural gas, Spain has some reserves but they are not as important as coal.

In Fig. 2 we can see the fossil fuel consumption over the 20th century in Spain; natural gas production is almost negligible. Despite domestic production, Spain still needs to import great quantities of fossil fuels. For example, in 2009, the degree for oil self-sufficiency in Spain was 0.18% and for natural gas it was 0.04% (CORES, 2009).

4.2. Non-fuel minerals

At the beginning of the century, copper extraction was one of the most important along some other metallic elements such as iron and lead (Fig. 3). Due to low ore grade, profitability and import easiness, this trend has changed towards exploitation of industrial minerals, like limestone and gypsum.

At the end of the 20th century, limestone was the most extracted material, with almost 200 million tonnes extracted in 2009, compared to the 8 million of tonnes of gypsum extracted that same year. If we study the cumulative production between 1900 and 2010, limestone accounts for 82% of the total amount.

Analysing the actual exergy replacement costs, b_t^*, potash is the substance that has more impact in the second half of the century, being almost 60% of the total exergy degradation costs in Spain, followed by limestone (12%) and copper (9%). In decreasing order, mercury, gypsum, gold and iron also have big impact on exergy replacement costs.

Of the 22 minerals studied, after gold, mercury has the highest value of unit exergy replacement (289,298 GJ/t), attributable to its low concentration in mines and the consequent use of energy to concentrate it. Even if the exergy loss of mercury was apparently not so remarkable, we can appreciate its relative importance in the exergy loss diagrams.

According to the depletion ratios calculated with the estimated mineral reserves, man has depleted in just one century around 45% of the non-fuel mineral reserves available in Spain. The most depleted minerals are: mercury, gold, antimony, manganese, lead, copper, bismuth, zinc, wolfram and fluorspar. These data must be taken only as an approximation due to the lack of accuracy of the reserves data in Spain and because of the limitations of the study.

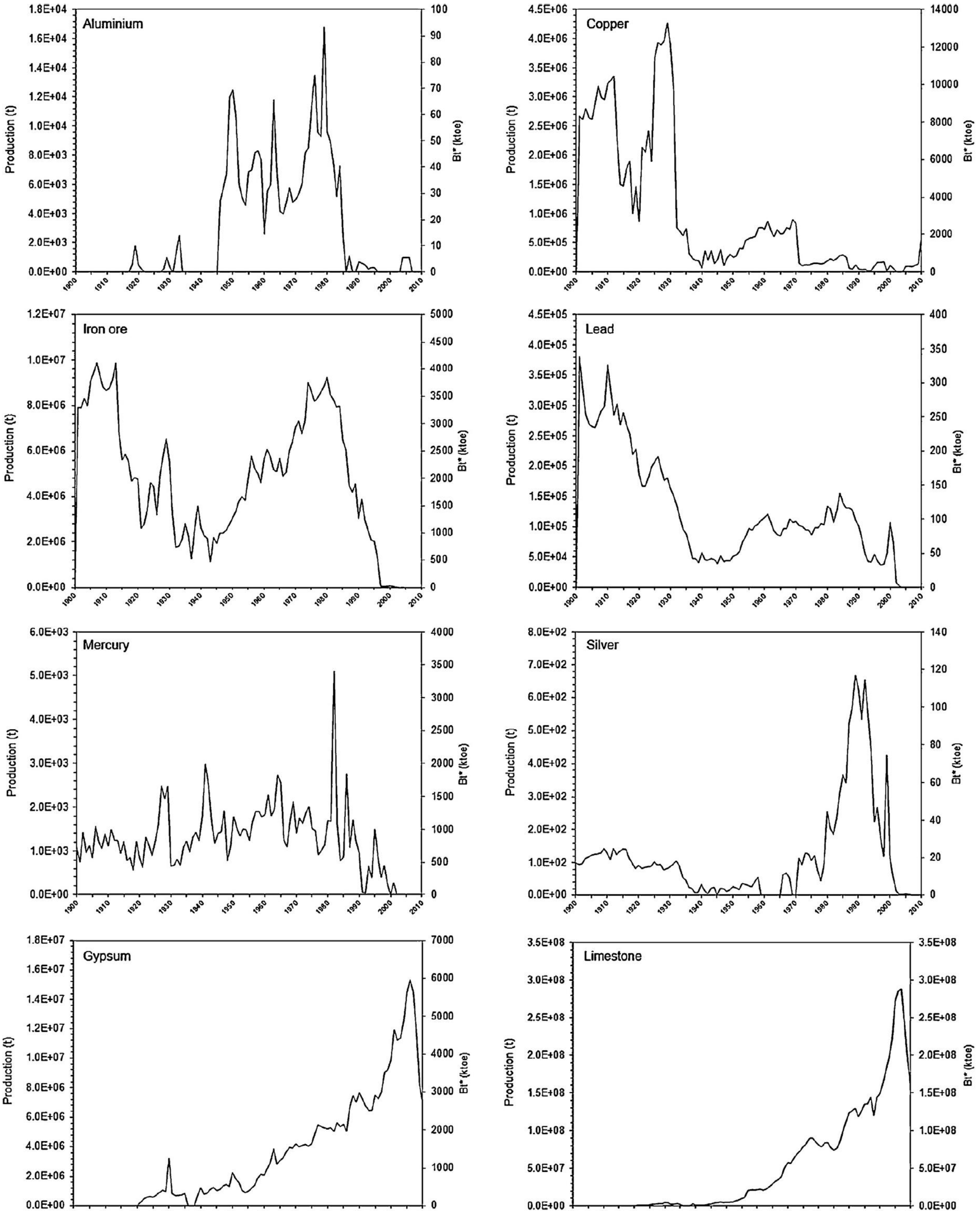

Fig. 3. Mineral extraction (in tonnes) and exergy loss (in ktoe) throughout the 20th century for selected minerals.

Table 1
Total exergy costs of 2009 Spanish mineral production. Values are expressed in Mtoe if not stated otherwise. Consumption = production + imports − exports (*t*).

Substance	2009 Spanish Production (*t*)	Replacement costs	Mining & conc.	Smelting & refining	Consumption (*t*)
Aluminium (bauxite)	0	–	–	–	3.51E + 06
Antimony	0	–	–	–	7.45E + 01
Bismuth	0	–	–	–	1.01E + 05
Cadmium	0	–	–	–	6.50E + 01
Copper	1.42E + 05	0.37	9.74E − 02	7.25E − 02	1.22E + 06
Fluorspar	1.16E + 05	0.50	4.00E − 03	–	1.16E + 05
Gold	0	–	–	–	–
Gypsum	8.18E + 06	3.00	3.93E − 02	–	8.21E + 06
Iron ore	0	–	–	–	4.22E + 06
Lead	0	–	–	–	−1.09E + 04
Limestone	1.95E + 08	12.15	1.68E + 00	2.68E + 01	1.95E + 08
Manganese	0	–	–	–	3.31E + 04
Mercury	0	–	–	–	4.68E + 02
Nickel (sulfides)	1.19E + 05	2.16	4.32E − 02	2.83E − 01	1.78E + 04
Potash	8.03E + 05	23.40	5.87E − 02	–	8.03E + 05
Silicon	7.89E + 05	0.01	4.46E − 02	4.70E + 00	2.61E + 06
Silver	0	–	–	–	6.61E + 01
Tin	0	–	–	–	−9.73.E + 01
Titanium (ilmenite)	0	–	–	–	1.14E + 03
Uranium	0	–	–	–	6.42E + 00
Wolfram	4.18E + 02	0.07	2.12E − 03	1.43E − 03	1.08E + 02
Zinc	0	–	–	–	8.69E + 05

4.3. *Mineral capital endowment in 2009*

Applying the exergoecology method to the extraction of minerals in Spain in the year 2009 we can see that the exergy replacement costs associated to mineral production was 41.67 Mtoe, 99.93% corresponding to the exergy replacement costs of industrial minerals, being potash, limestone and gypsum the minerals with higher exergy replacement costs.

As it can be seen on Table 1, the vast majority of the metallic minerals were not extracted during 2009, but they were included in this study due to their historical importance throughout the 20th century. We also have calculated exergy needed for mining, concentration, smelting and refining for the extracted commodities.

If we take into account the imports and exports of the aforementioned 22 substances only and we calculate the material consumption, production plus imports minus exports, we have that the total exergy replacement cost changes from 98.97 Mtoe, if we don't take into account recycling rates, to 73.39 Mtoe, if we take into account recycling rates (Annexes, Table A.2). This corresponds roughly to the average coal domestic consumption in Spain for 4 years.

In the case of fossil fuels, if we add the imports to the Spanish production, the total exergy the exergy replacement costs 94.15 Mtoe, where 93% corresponds only to imports. In that year, 13.7% of the oil imports came from Iran, 13.1% from Russia and 12.7% from Libya (CORES, 2009). Since Spanish production that year was very low compared to the imports, we can consider that the entire exergy cost is lost in the supplying countries.

Since the data of the year 2009 are the most accurate and complete ones, we can represent the distribution of the exergy replacement costs taking into account extraction, imports, exports and recycling rates for the 22 substances analysed and for the three fossil fuels (Fig. 4). We are going to assume that all mineral and fossil fuels that are not exported or recycled were consumed within the country that year.

We can see that imports are 76% of the total value of the exergy replacement costs in 2009. This is mainly due to the influence of fossil fuels imports, since exergy replacement cost are really elevated. Also that the exergy replacement costs for exports and recycling is approximately 13% of the total value. This also demonstrates that Spain is a consuming country, since almost all that exergy is aimed to domestic consumption.

From Fig. 4 and the data in Table 2 we can see that Spanish domestic production of minerals is quite low and that it is fundamentally an importing country, notably in the case of fossil fuels. All the commodities are almost fully consumed within the country if we look at the export ratios, being gypsum and silicon the most exported materials. Recycling rates are significantly low for all the metallic minerals. Even if aluminium, iron or copper are recycled, there are still many other substances that could be reintegrated into the system to avoid future extraction, and we can see that the total amount of materials recycled in Spain in 2009 was not very significant compared to the domestic material consumption.

If we do a comparison between the results in exergy replacement costs and the production plus imports in tons for the same materials, we can see that the relative importance of fossil fuels

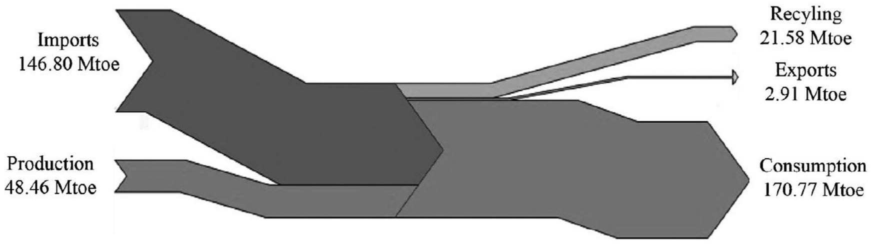

Fig. 4. Flow diagram with the exergy distribution for fossil fuels and non-fossil fuels minerals for year 2009.

Table 2
Distribution of Spanish mineral capital in 2009.

	Production (t)	DMC$^{(1)}$ (Mtoe)	Imports (Mtoe)	Exports (Mtoe)	Recycling (Mtoe)
22 non-fuel minerals	2.05E+08	117.68	59.45	2.91	21.58
Fossil fuels	9.81E+06	94.15	87.36	–	–
Total	2.15E+08	211.82	146.80	2.91	21.58

(1) Domestic material consumption: production + imports – exports + recycling.

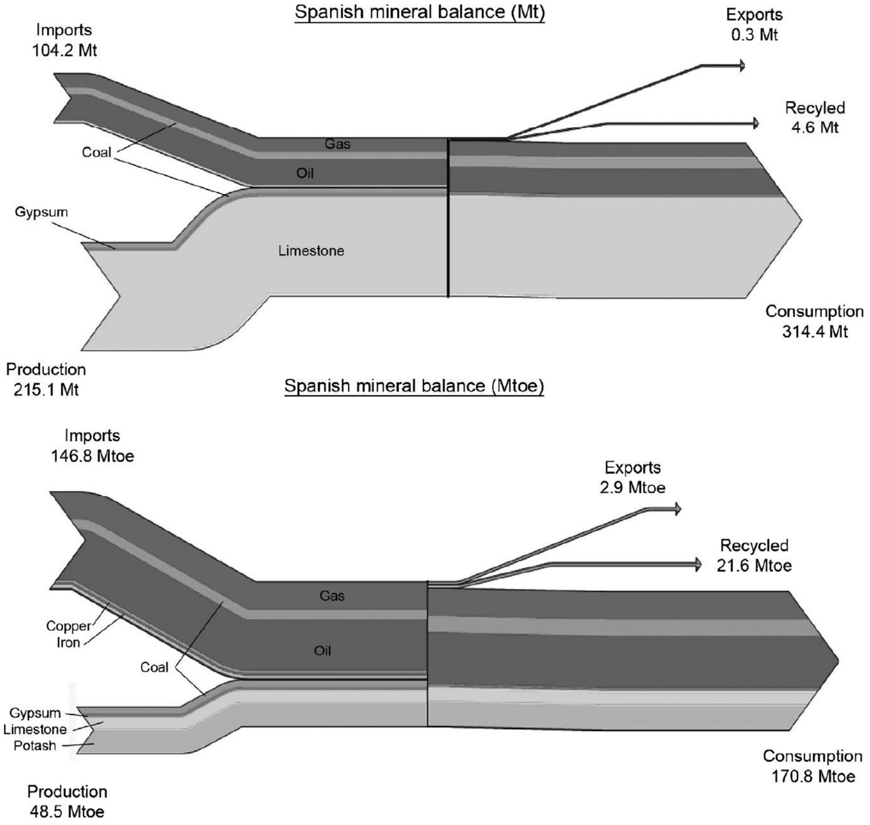

Fig. 5. Spanish mineral balance in 2009 expressed in tons and in exergy replacement costs.

and minerals is reversed. We can see that fossil fuels are more relevant for the loss of natural resources, but we must always have in mind that this study only takes into account a limited number of minerals.

In Fig. 5, we can see the material flow with a Sankey diagram in tons and in exergy replacement costs (Valero et al., 2013). With exergy replacement costs not only the amount of the commodity produced but also the scarcity degree, calculated as the effort required replacing the minerals, are taken into account. This reversed importance of exergy loss and production is a direct consequence of the unit exergy cost, which depends on the amount of energy needed for mining (extraction and mining and concentration processes) and ore grade. In the case of industrial minerals all the extracted material is profitable, so even if the production is

Table 3
Monetary replacement costs of the main mineral reserves depletion in Spain due to mineral extraction, consumption and net balance for 2009.

	Exergy (Mtoe)	Market Price	Price ($US/toe)	Extraction monetary exergy replacement cost (M€)	Consumption monetary exergy replacement costs (M€)	Net Monetary exergy replacement costs in the rest of the world (M€)	% GDP		
				(1)	**(2)**	**(3)=(2)-(1)**	**(1)**	**(2)**	**(3)**
Coal	6.7	70.66 $US/tonne	130.6	626.2	742.5	116.2	0.06	0.07	0.01
Oil	0.1	61.67 $US/barrel	414.8	30.9	15,583	15,552	0.00	1.49	1.48
Natural gas	0.0	4.85 $US/million	192.5	0	3161	3161	0.06	0.30	0.30
Non-fuel minerals	41.67		130.6–618.7	2715–12,861	7920–37,520	5205–24,659	0.26–1.22	0.75–3.58	0.49–2.35
Total	**48.47**			**3272–13,518**	**27,408–57,008**	**24,036-43,486**	**0.31-1.28**	**2.61-5.43**	**2.29-4.14**

Table 4

Exergetic and monetary extraction and replacement costs for non-fuel minerals. The consumption value for lead is apparently negative since for 2009 the exports exceeded extraction+imports. The zinc imports usually contain a not negligible amount of lead, but that lead is not accounted for in the statistics. This material, zinc and lead, after being treated in Spain is exported, hence that negative value.

Substance	Bonus (unit exergy cost) (GJ/ton)	Mining and concentration energy (GJ/ton)	Refining energy (GJ/ton)	CE (mining + refining)	CR (bonus + CE)	CR/CE	Price $/t (1)	Price $/t (2)	Extraction value with current resource prices (M€) (3)	Extraction value obtained with replacement costs (M€) (3)	Consumption value with current resource prices (M€) (3)	Consumption value with replacement costs (M€) (3)
Aluminium (Bauxite)	627.34	10.55	23.87	34.42	661.76	19.23	1750	33,648	0	0	4398	84,564
Antimony	474.49	1.40	12.00	13.40	487.89	36.41	5190	188,966	0	0	0	0.0
Bismuth	489.22	3.60	52.80	56.40	545.62	9.67	17,300	167,362	0	0	1	5.8
Cadmium	5,898.41	263.92	278.52	542.43	6440.84	11.87	2870	34,078	0	0	0	0.0
Copper	110.38	28.82	21.45	50.26	160.64	3.20	5320	17,002	541.6	1731	4638	14,822.9
Fluorspar	182.66	1.45	0.00	1.45	184.11	126.97		0	0	0	0	0.0
Gold	583,668.40	107,751.82	0.00	107,751.82	691,420.22	6.42	31300,000	200845,360	0	0	0	0.0
Gypsum	15.41	0.20	0.00	0.20	15.61	77.28	18	1376	104.4	8069	104	8068.8
Iron ore	17.75	0.70	13.43	14.13	31.88	2.26	94	211	0	0	283	639.1
Lead	36.62	0.89	3.28	4.17	40.80	9.77	1920	18,765	0	0	−15	−147.3
Limestone	2.62	0.36	5.76	6.12	8.74	1.43		0	0	0	0	0.0
Manganese	15.64	0.16	57.44	57.61	73.25	1.27	1370	1742	0	0	33	41.3
Mercury	28,298.00	157.00	252.00	409.00	28,707.00	70.19	17,400	1221,276	0	0	0	0.0
Nickel (sulfides)	761.03	15.50	100.00	115.50	876.53	7.59	14,600	110,802	1245.6	9453	186	1411.9
Potash	1224.21	3.07	0.00	3.07	1227.28	399.63	737	294,530	423.9	169,442	424	169,442.3
Silicon	0.73	0.72	76.00	76.72	77.45	1.01		0	0	0	0	0.0
Silver	7371.41	1281.42	284.76	1566.18	8937.59	5.71	472,000	2693,523	0	0	0	0.0
Tin	426.35	15.23	11.36	26.60	452.95	17.03	14,100	240,119	0	0	−1	−16.7
Titanium (ilmenite)	4.51	7.25	128.14	135.39	139.90	1.03	15,600	16,120	0	0	13	13.2
Uranium	901.40	188.77	0.00	188.77	1090.17	5.78		0	0	0	0	0.0
Wolfram	7429.28	213.00	144.00	357.00	7786.28	21.81	25,700	560,525	7.7	168	2	43.3
Zinc	24.79	1.49	40.41	41.90	66.69	1.59	1720	2738	0	0	1072	1706.0
								Total	**2323**	**188,863**	**11,137**	**280,594**
								%GDP	**0.22**	**18.62**	**1.06**	**26.77**

Note: Price (2)=Price (1) × (CR/CE). See text. (3) Based on values for Spanish extraction and consumption in 2009.

large, if we compare it to the production and exergy costs of copper or wolfram, we can see that the latter are more significant in relative exergy terms due to scarcity.

In the case of fossil fuels, since once they are burned they cannot be recovered, their exergy replacement costs are substantially more important than those of the non-fuel minerals.

4.4. Conversion of exergy costs into monetary costs

We are going to estimate the monetary costs of the main mineral reserve depletion due to mineral extraction in Spain during the year 2009. Converting the exergy costs into monetary costs through energy price is another option to present the results obtained in a more understandable way. Monetary value for fuel minerals can be directly calculated with their corresponding prices of the year under consideration, in this case, 2009, taken from the British Petroleum statistics. According to the BP Statistical Report (2010), the average price of oil in 2009 was 61.67 $US/barrel, the average price of natural gas was 4.85$US/million Btu and the average price of coal was 70.66 $US/tonne. Since all the calculations are going to be done in euros, we are going to use the US dollar-euro currency exchange rate for 2009, being 1.3948 (official data from Bank of Spain).

For non-fuel minerals, as stated before, we are going to consider a lower bound, calculated assuming that coal is used to replace the mineral capital (70.66 $US/tonne), and an upper bound considering we are using electricity at a price of 38€/MWh (Red Eléctrica de España) using the average price for electricity for 2009 in Spain.

Table 3 shows an estimation of the monetary costs associated with the depletion of mineral reserves due to mineral extraction and consumption in 2009. Depending if the energy source chosen for replacing the mineral capital is in form of coal or electricity, the monetary equivalent of mineral depletion by extraction would be of 3272 to 13,518 M€. If we take into account the total mineral consumption, also including the net flows from the rest of the world, the monetary equivalent would be between 27,408 and 57,008 M€. Since Spanish GDP in 2009 was 1048 billion of euros according to the Spanish National Statistical Institute (I.N.E.), this means that the aforementioned loss of mineral capital is equivalent to between 0.31 and 1.28% of the Spanish GDP in 2009. This percentage would be even larger when other non-fuel minerals imported and exported by Spain were considered. In this case, given the actual energy prices, the depletion of mineral resources would be equivalent of 2.61 to 5.43% of Spanish GDP. These percentages show to what extent the mineral depletion caused by Spanish economy is based on resources from the rest of the world.

Although we take into account the Spanish GDP as a monetary unit measure for obtaining an order of magnitude to compare the monetary cost of mineral loss and depletion, we can also compare these monetary results in a different way. For example, according to I.N.E. (Spanish Statisfical Office), the metallurgy and resource sector contributed to 18,384 million of euro in 2009 (1.8% of the GDP). If all responsibility of compensating the minerals depletion due to economic activity would be assumed by this sector, it would mean that its contribution (gross value added, GVA) to GDP could lead to a neutral or even negative balance, meaning that the costs of irreversibly losing the Spanish mineral capital would be the same or more as the gross value added it gets for its resources. However, the loss of mineral capital, meaning the replacement costs of non-fuel minerals, is not considered in these accounts. If this replacement costs were considered, then the mineral prices used by this sector regarding saleable production would also be very different from the current ones.

The actual mineral prices incorporate, among other things, the energy extraction costs (around 10% of saleable production). With the relationship between extraction/replacement costs for every mineral, we can estimate (*ceteris paribus*) what the mineral price would be if we were taking into account the exergy replacement costs in this price. What would be then the total production value of mineral extracted or consumed? How much should the society pay for these resources compared to the level of GDP or national income?

According to Table 4, if we assume that the proportions of other components incorporated in resource price (labour costs, financial costs, rate of profit, etc.,) remain constant over time, then a rise of energetic costs (e.g. exergy required to restore the depleted resources) would imply a proportional increment of the resource price (given the actual energy price). Price (2) in Table 4 is a *theoretical* price estimated under this hypothesis. As we can see, by using price (2) and applying replacement costs to estimate the production (extraction) value, the result would be 188,863 M€, that is, an equivalent of 18.62% of Spanish GDP and 84 times higher than the value obtained with actual and current resource prices (2323 M€). On the other hand, if we estimate the resource consumption (extraction + imports – exports) value with the same method, the monetary value would be 280,594 M€, which represents an equivalent of 26.77% of Spanish GDP and is 25 times higher than the value estimated with actual and current resource prices (11,137 M€).

These are obviously theoretical results, but they allow us to see the distance between situations in which resources are treated as ordinary goods whose price is dependent of production (extraction) costs, and situations in which they are treated as a physical asset that needs to be replaced to meet the objective of sustainable development. It should be stated that the numbers obtained depend strongly on commodity prices and the choice of energy source used for the monetary calculation of the replacement costs of non-fuel minerals. This fact is a clear indication that assessing mineral wealth loss in monetary terms should not necessarily be the final objective, as the volatility and arbitrariness of prices distorts their real physical value. Furthermore, physical values are absolute and understandable, without exception, worldwide. That said, monetary values do provide an order of magnitude as to the importance of a given mineral's extraction. Consequently, we propose an estimation of the physical distance and a rough approach of its monetary costs. After quantifying the costs, determining what part of society should pay for these costs is a different issue that deserves important and urgent attention.

5. Conclusions

Analyzing exergy replacement costs has proved to be a very useful tool to study the mineral balance of a country and also a good indicator to assess mineral resource sustainability. Usually other methods for natural resources accounting only take into account the total amount of extraction in tons instead of the scarcity of the materials that are being studied. With the method used in this paper, we can infer that scarcity and ore grade is a critical parameter and that production of gold or copper cannot be compared with production of limestone. With the exergy replacement costs we can obtain a more realistic value of the loss of natural capital of a country.

An estimation of the monetary costs associated with the depletion of mineral reserves due to mineral extraction and consumption in 2009 would be between 3272 and 13,518 M€, and if we take into account the total mineral consumption (extraction + imports – exports), the monetary equivalent would be of 27,408 to 57,008 M€. Since Spanish GDP in 2009 was 1048 billion of euros, this would mean that the aforementioned loss of mineral resources would be equivalent to between 0.31 and 1.28% of the

Spanish GDP in 2009 in the first case and between 2.61 and 5.43% in the second one.

Starting from the current price of minerals we can estimate, with the relationship between extraction/replacement costs for every mineral, what the mineral price would be if we were taking into account the exergy replacement costs in the current price under this hypothesis. The result for saleable production of the minerals extracted in 2009 in Spain with this theoretical price would be 188,863 M€, that is an equivalent of 18.62% of Spanish GDP and 84 times higher than the value obtained with actual and current resource prices (2323 M€). On the other hand, if we estimate the exergy replacement cost of resource consumption (extraction + imports – exports), the monetary value would be 280,594 M€, which represents an equivalent of 26.77% of Spanish GDP and is 25 times higher than the value estimated with actual and current resource prices (11,137 M€).

Even if these are theoretical results, we can see the difference between a situation where resources are treated as ordinary goods and another one where the replacement costs are taken into account, moving towards a more sustainable development model. Since Earth is not an infinite reservoir for mineral capital, this overuse and over extraction cannot be maintained at long-term and it is important to find a way to reflect this mineral loss in the market prices. With more studies like the present one we can try to identify where the largest exergy losses are located with the aim at finding more sustainable solutions.

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Appendix A. Annexes

Tables A.1 and A.2.

Table A.2
Recycling rates according to the report about Recycling Rates Metals done by the United Nations Environment Programme (2012).

Substance	Recycling rate (%)
Aluminium	35
Antimony	15
Cadmium	76
Copper	47
Iron	56
Lead	95
Mercury	97
Nickel	41
Tin	50
Titanium	11
Wolfram	40
Zinc	35

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Table A.1
Exergy replacement costs of the 22 non-fuel minerals. Values are expressed in GJ/ton of substance.

Substance	Mineral ore	K ($x = x_c$)	Bonus(1)	M & C(2)	S & R(3)	Unit value (2009) ($/t)(4)
Aluminium	Gibbsite	2088.1	627.3	10.55	23.87	1750
Antimony	Stibnite	3929.3	474.5	1.4	12.0	5190
Bismuth	Bismuthinite	7859.2	489.2	3.6	52.8	17,300
Cadmium	Greenockite	39,229.8	5898.4	263.9	278.5	2870
Copper	Chalcopyrite	525.0	110.4	28.8	21.4	5320
Fluorspar	Fluorite	582.4	182.7	1.5	0.0	N.A.
Gold	Native gold	638,0356.5	583,668.4	107,751.8	0.0	31300,000
Gypsum	Gypsum	117.6	15.4	0.2	0.0	17.8
Iron	Hematite	164.5	17.8	0.7	13.4	93.6
Lead	Galena	384.3	36.6	0.9	3.3	1920
Limestone	Calcite	12.9	2.6	0.4	5.8	N.A.
Manganese	Pyrolusite	37.4	15.6	0.2	57.4	1370
Mercury	Cinnabar	209,116.2	28,298.0	157.0	252.0	17,400
Nickel	Pentlandite	13,039.0	761.0	15.5	100.0	14,600
Potash	Sylvite	1926.0	1224.2	3.1	0.0	737
Silicon	Quartz	6.3	0.7	0.7	76.0	N.A.
Silver	Argentite	112.85	7371.4	1281.4	284.8	472,000
Tin	Cassiterite	2704.2	426.4	15.2	11.4	14,100
Titanium	Ilmenite	172.3	4.5	7.2	128.1	15,600
Uranium	Uraninite	13,843.3	901.4	188.8	0.0	N.A.
Wolfram	Scheelite	69,721.3	7429.3	213.0	144.0	25,700
Zinc	Sphalerite	104.3	24.8	1.5	40.4	1720

(1) Exergy replacement costs.
(2) Mining and concentration energy.
(3) Smelting and refining energy.
(4) Data according to USGS.

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4.4. COMPLEMENTARY RESULTS

In this section, complementary results for the already published paper on monetary costs related to mineral depletion for Spain are presented.

The monetary costs of the main mineral reserve depletion due to mineral extraction in Spain during the 2000-2012 period have been estimated in this section. Converting exergy replacement costs into monetary costs through energy price is a suitable alternative to present the results obtained in a more direct and understandable way.

Monetary value for fossil fuels can be directly calculated with their corresponding market prices of the years under consideration. In this case the prices for coal, natural gas and oil have been taken from the British Petroleum statistics (Table 13). For non-fuel minerals, we are going to consider two boundaries. A lower one, calculated assuming that coal is used to re-concentrate the dispersed mineral capital, and an upper one considering that this same activity is carried out using electricity (Red Eléctrica de España) using the average price for electricity for each year in Spain in €/MWh. As all the calculations are going to be done in dollars, the average US dollar-euro currency exchange rate for every year is also needed to obtain the final prices (Banco de España, 2015). These numbers will be then compared to the GDP corresponding to the extractive sector in Spain (Instituto Nacional de Estadistica, 2013) to analyze if the extracted natural resources in Spain are being assessed properly.

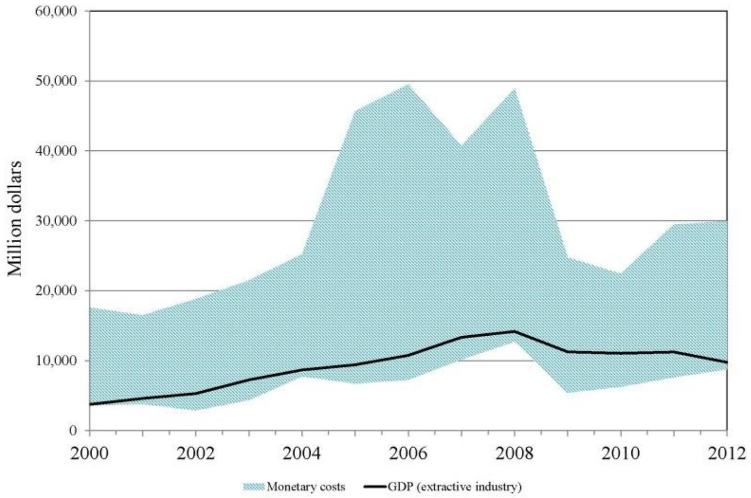

Figure 27. Monetary costs associated to Spanish mineral extraction and GDP corresponding to the extractive sector from 2000 to 2012.

Figure 26 represents the monetary costs associated with Spanish mineral extraction (non-fuel minerals plus fossil fuels) from 2000 to 2012, showing the area ranging from the lower to the upper boundaries. The GDP corresponding to the extractive sector has also been represented in the diagram for comparative purposes. The electricity price in Spain experienced some drastic changes, for example the average final price in 2005 was 75.1% higher than in 2004. For this reason several fluctuations can be appreciated in the upper boundary of the estimated monetary costs associated to mineral depletion.

Table 15 shows the total exergy replacement costs associated to mineral extraction in Spain from the years 2000 to 2012 and their corresponding minimum and maximum monetary costs. These monetary costs represent in the most extreme cases between 0.42 and 4.03 of the total Spanish GDP.

Table 15. Total exergy replacement costs and monetary costs associated to mineral extraction in Spain from 2000 to 2012.

Monetary costs and GDP$_{extr}$ are in billion dollars.

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
ERC (total)	53.68	52.20	48.92	53.92	58.05	59.87	60.92	61.75	46.42	42.15	36.40	33.77	50.67
Monetary costs (min)	3.60	3.80	2.90	4.38	7.77	6.74	7.26	10.18	12.72	5.42	6.27	7.63	8.74
Monetary costs (max)	17.59	16.48	18.79	21.47	25.20	45.65	49.50	40.71	48.90	24.75	22.42	29.48	30.75
% GPD$_{min}$	0.62	0.43	0.42	0.49	0.75	0.59	0.59	0.71	0.79	0.37	0.45	0.52	0.66
% GPD$_{max}$	3.02	1.88	2.73	2.42	2.43	4.03	4.00	2.82	3.06	1.70	1.62	2.02	2.32
GPD$_{extr}$	3.74	4.60	5.30	7.26	8.67	9.41	10.76	13.35	14.17	11.26	11.05	11.24	9.75

When comparing the monetary costs with the GDP generated by the extractive sector (GDP$_{extr}$) we can see that in the best case scenario, the lower limit, the benefits generated by the extractive sector can approximately compensate the mineral capital loss. In the worst case scenario, the upper limit, the monetary costs associated to mineral loss are two to five times higher than the GDP generated by those same resources, meaning that Spanish domestic resources are not being evaluated properly.

According to *Instituto Nacional de Estadística (*I.N.E.), the extractive sector contributed to 9,753 million dollar in 2012 (0.74% of the total GDP). Converting the exergy replacement costs into monetary costs for that same year results in a range from 8,744 to 30,748 million dollar associated to mineral depletion. If all responsibility of compensating the minerals depletion due to economic activity would be assumed by this sector, it would mean that its contribution to GDP could lead to an almost neutral to a negative balance, meaning that the costs of irreversibly losing the Spanish mineral capital would be the same or more as the gross value added it gets for its resources. However, the loss of mineral capital, meaning the replacement costs of non-fuel minerals, is not considered in these accounts. If this replacement costs were considered, then the mineral prices used by this sector regarding saleable production would also be very different from the current ones.

In Table 16, Price (1) represents the actual price in 2009 of each commodity and Price (2) in which is the theoretical price estimated under the aforementioned hypothesis.

From the Price (2) data we can appreciate that there is commodity whose price is approximately 400 times the actual price for the year under consideration, going from 737 $/t to 294,530 $/t, that is the case of potash. Other minerals whose unit value increases drastically when exergy replacement costs are considered in the accountings are cobalt (79 times), gypsum (77 times) and mercury (70 times). By contrast, there are other commodities whose price does not substantially change; such is the case of silicon, titanium, phosphate rock, chromium, manganese and zinc.

With Price (1) and (2) for each substance we can calculate the total value of the mineral production in Spain for the year 2009. Taking into account exergy replacement costs into the calculations, the production value in Spain would be 156,246 million dollar, approximately 68 times higher than when using the actual and current resource prices (2,294 million dollar). In other words, 10.70% and 0.16% respectively of the Spanish total GDP for 2009.

These are obviously only theoretical results, but they allow us to see the distance between situations in which resources are treated as ordinary goods whose price is dependent of production (extraction) costs, and situations in which they are treated as a physical asset that needs to be replaced to meet the objective of sustainable development.

Table 16. Exergy replacement costs and unit value for selected non-fuel minerals for the year 2009.
EC = extraction cost; RC = replacement cost; ERC = exergy replacement costs; Price (1) - Source USGS; Price (2) = Price (1) * (CR/CE).

Minerals	Exergy replacement costs [GJ/ton]	Mining and concentration energy [GJ/ton]	Refining energy [GJ/ton]	EC (mining + refining)	RC (ERC + EC)	RC/EC	ERC/EC	Price (1) [$/t]	Price (2) [$/t]
Aluminium	627.34	10.55	23.87	34.42	661.76	19.23	18.23	1,750	33,648
Antimony	474.49	1.40	12.00	13.40	487.89	36.41	35.41	5,190	188,966
Arsenic	399.84	9.00	19.00	28.00	427.84	15.28	14.28	582	8,893
Barite	-	-	-	-	-	-	-	85	-
Bismuth	489.22	3.60	52.80	56.40	545.62	9.67	8.67	17,300	167,362
Cadmium	5,898.41	263.92	278.52	542.43	6,440.84	11.87	10.87	2,870	34,078
Chromium	4.54	0.10	36.30	36.40	40.94	1.12	0.12	2,030	2,283
Cobalt	10,871.93	9.20	129.00	138.20	11,010.13	79.67	78.67	34,200	2,724,647
Copper	110.38	28.82	21.45	50.26	160.64	3.20	2.20	5,320	17,002
Feldspar	-	-	-	-	-	-	-	84	-
Fluorspar	182.66	1.45	0.00	1.45	184.11	126.97	125.97	-	-
Gold	583,668.40	107,751.82	0.00	107751.82	691,420.22	6.42	5.42	31,300,000	200,845,360
Graphite	-	-	-	-	-	-	-	897	-
Gypsum	15.41	0.20	0.00	0.20	15.61	77.28	76.28	18	1,376
Iron ore	17.75	0.70	13.43	14.13	31.88	2.26	1.26	94	211
Lead	36.62	0.89	3.28	4.17	40.80	9.77	8.77	1,920	18,765
Limestone	2.62	0.36	5.76	6.12	8.74	1.43	0.43	-	-
Lithium	545.83	12.50	420.00	432.50	978.33	2.26	1.26	4,530	10,247
Magnesite	-	-	-	-	-	-	-	-	-
Manganese	15.64	0.16	57.44	57.61	73.25	1.27	0.27	1,370	1,742
Mercury	28,298.00	157.00	252.00	409.00	28,707.00	70.19	69.19	17,400	1,221,276

Minerals	**Exergy replacement costs [GJ/ton]**	**Mining and concentration energy [GJ/ton]**	**Refining energy [GJ/ton]**	**EC (mining + refining)**	**RC (ERC + EC)**	**RC/EC**	**ERC/EC**	**Price (1) [$/t]**	**Price (2) [$/t]**
Molybdenum	907.91	136.00	12.00	148.00	1055.91	7.13	6.13	25,800	184,071
Nickel	761.03	15.50	100.00	115.50	876.53	7.59	6.59	14,600	110,802
Phosphate rock	0.35	0.30	4.60	4.90	5.25	1.07	0.07	124	133
Potash	1,224.21	3.07	0.00	3.07	1,227.28	399.63	398.63	737	294,530
Salt	44.07	3.30	39.60	42.90	86.97	2.03	1.03	41	82
Silicon	0.73	0.72	76.00	76.72	77.45	1.01	0.01	1,670	1,686
Silver	7,371.41	1,281.42	284.76	1,566.18	8,937.59	5.71	4.71	472,000	2,693,523
Talc	-	-	-	-	-	-	-	-	-
Tin	426.35	15.23	11.36	26.60	452.95	17.03	16.03	14,100	240,119
Titanium	4.51	7.25	128.14	135.39	139.90	1.03	0.03	15,600	16,120
Uranium	901.40	188.77	0.00	188.77	1,090.17	5.78	4.78	-	-
Wolfram	7,429.28	213.00	144.00	357.00	7,786.28	21.81	20.81	25,700	560,525
Zinc	24.79	1.49	40.41	41.90	66.69	1.59	0.59	1,720	2,738
Zirconium	654.43	738.50	633.00	1,371.50	2,025.93	1.48	0.48	830	1,226

5. CASE STUDIES

To validate the Physical Geonomics methodology at the macro-level, several case studies have been chosen:

- Spain: thermodynamic assessment of mineral depletion and trade
- Europe: assessment of EU-28 mineral trade
- Comparative analysis between an importing and an exporting country: Colombia vs. Spain

For each of them different data sources have been used to gather the data of tonnes extracted, imported and exported in each case. Subsequently, the data in tonnes has been converted into exergy replacement costs and then to economic costs.

The main results and conclusions of this subsection are fully developed in the following papers:

- Calvo, G., Valero, A., Valero, A., Carpintero, Ó. (2015). **An exergoecological analysis of the mineral economy in Spain.** *Energy*, 88, 2-8.

- Calvo, G., Valero, A., Valero, A, (2016). **Material flow analysis for Europe. An exergoecological approach.** *Ecological Indicators*, 60, 603-610.

- Calvo, G., Valero, A., Carmona, L.G and Whiting, K. **Physical assessment of the mineral capital of a nation: the case of an importing and an exporting country**. *(Sent to Resources - ISSN 2079-9276).*

5.1. DATA SOURCES

Although mineral dispersion and depletion is gradually becoming a crucial issue for our economies, it is surprising the lack of reliable data on this subject. Information on both extraction and existing mineral reserves is not always up to date. Not all the databases use the same criteria to present the results and obtaining comparable data is not always possible. Additionally the lack of in-depth studies on this matter makes it really difficult to obtain accurate data. Therefore, to accomplish the assessment of mineral resources in Spain, European Union and Colombian, multiple databases have been used to gather information about mineral extraction and trade.

In Spain, since 1856 and to this day, there is an annual report on mining statistics that collects information on the mining sector produced by the Ministry of Industry of Spain (Estadistica Minera de España). After a thoroughly selection and revision process, extraction data for selected mineral substances from 1900 to 2012 has been compiled. Moreover, the domestic extraction data has been compared with the annual reports carried out by reliable institutions such as Geological and Mining Institute of Spain (Instituto Geológico y Minero de España, various years) and United States Geological Survey (Newman, various years; Gurmendi, various years). Additionally, for the most recent years, these mining statistics have also being compared and complemented with sustainability and annual reports for the different mining companies (Cobre Las Cruces S.A., various years; Lundin Mining Corporation, various years). Import and export data have been obtained from the Statistics National Service (*Instituto Nacional de Estadística*), from the databases of foreign trade from (*Cámara de Comercio de España)* and from the Ministry of Industry, Energy and Tourism of Spain (MINETUR) statistics services.

To better understand the position and situation of Spain in the European Union, a general study of the European Union (EU-28) mineral trade has been accomplished for the 1995-2012 period, with a detailed analysis carried out for the years 2001 and 2011. Information regarding domestic production, imports and exports for each of the 28 member states of the European Union has been obtained from British Geological Survey mineral statistics (British Geological Survey, 2005, 2010, 2014a) and completed with statistics from selected national services from some European countries. Statistics from the British Geological Survey include information on many non-fuel minerals, but only a selection of them were considered in the study.

Regarding recycling rates of metallic minerals, both for Spain and for the European Union as a whole, an assumption has been made using United Nations Environment Programme (UNEP) average recycling rates data as individual data for recycling rates of each of the member states of the European Union was not available (UNEP, 2011b).

Furthermore, as Spain is a country with several geological limitations regarding mineral availability, a comparative analysis has been carried out between Spain and Colombia. This analysis, comparing a supposedly importing country versus an exporting country, has been used to state the differences between the mineral trade situation in both countries. For the Colombian case only the minerals considered as priority minerals by the Colombian National Government due to their contribution to the GDP (gold, silver, platinum, nickel, copper, iron, limestone, coal, oil and gas) have been used (Carmona et al., 2015). Information about Colombian mineral extraction has been gathered from the Ministry of Mines and Energy of Colombia, the Mining System of Information of Colombia and British Petroleum (British Geological Survey, 2014b; SIMCO, 2011). Information of imports and exports has been additionally compiled from the Mining System of Information of Colombia.

5.2. MATERIAL FLOW ANALYSIS

So far the information that has been gathered is expressed only in mass terms. Considering the different values of exergy replacement costs (ERC) of each substance (Table 1), meaning the exergy required to return a resource from a dispersed state to the conditions found in nature with current technology, it seems logical that one tonne of limestone should not have the same weight in the calculations as one tonne of gold. Hence, to better assess mineral resources the data in tonnes has to be converted into exergy using Physical Geonomics. As explained above, with exergy replacement costs not only is the amount of the commodity produced relevant but also the scarcity degree, calculated as the effort required to replace the considered mineral.

As we rely on data of unit exergy costs, concentrating, smelting and refining exergies obtained in previous researches, we can only analyze approximately half of the total mineral production in Spain and Europe. In the case of the comparative analysis between Spain and Colombia only a selection of critical minerals has been included in the latter case. The substances that were analyzed for each case are listed in Table 17 along with their correspondent exergy replacement costs expressed in GJ/t.

For simplification purposes, it has been assumed that each substance is extracted only from one mineral ore. Even if this methodology has some limitations, we also have to take into account that the most important minerals for developing societies are included in this study.

Table 17. Exergy replacement costs (ERC) of the non-fuel minerals taken into account in each comparative study (Valero & Valero, 2014).

Substances	**Mineral ore**	**ERC [GJ/t]**	**Spain**	**Europe**	**Colombia**
Aluminium	Gibbsite	627.3	X	X	
Antimony	Stibnite	474.5	X	X	
Arsenic	Arsenopyrite	399.8	X	X	
Barium	Barite	-		X	
Bismuth	Bismuthinite	489.2	X	X	
Boron	Kernite	-		X	
Cadmium	Greenockite	5,898.4	X	X	
Chromium	Chromite	4.5	X	X	
Cobalt	Linaeite	10,871.9	X	X	
Copper	Chalcopyrite	110.4	X	X	X
Feldspar	Orthoclase	-		X	
Fluorspar	Fluorite	182.7	X	X	
Gold	Native gold	583,668.4	X	X	X
Gypsum	Gypsum	15.4	X	X	
Indium	*In* in *Zn* ores	-		X	
Iron ore	Hematite	17.8	X	X	X
Lead	Galena	36.6	X	X	
Limestone	Calcite	2.6	X	X	X
Lithium	*Li* in brines	545.8	X	X	
Magnesium	Magnesite	-		X	
Manganese	Pyrolusite	15.6	X	X	
Mercury	Cinnabar	28,298.0	X	X	
Molybdenum	Molybdenite	907.9	X	X	
Nickel	Pentlandite	761.0	X	X	X
Phosphate rock	Fluorapatite	0.4	X	X	
Potassium	Sylvite	1,224.2	X	X	
Selenium	*Se* in *Cu* ores	-		X	
Silicon	Quartz	0.7	X	X	
Silver	Argentite	7,371.4	X	X	X
Sodium	Halite	44.1	X	X	
Tantalum	Tantalite	482,827.9		X	
Tin	Cassiterite	426.4	X	X	
Titanium	Ilmenite	4.5	X	X	
Uranium	Uraninite	601.4	X	X	
Wolfram	Scheelite	7,429.3	X	X	
Zinc	Sphalerite	24.8	X	X	
Zirconium	Zircon	654.4	X	X	

In the case of fossil fuels, as once they are consumed and burned they cannot be replaced, only their chemical exergy has been considered and this exergy can be approximated to their High Heating Values (HHV). However, to make the calculations as accurate as possible, values of fossil fuel exergy previously obtained were used in this study (Table 18). These exergy values were calculated assuming an average composition for different types of coal, oil and natural gas (Valero & Arauzo, 1991) using the methodology described in Lozano & Valero (1988).

Table 18. Exergy of selected fossil fuels (Valero & Valero, 2012a).

Fuel	**HHV**	**Exergy [MJ/ton]**
Anthracite	30,675	31,624
Bituminous	28,241	29,047
Subbituminous	23,590	24,276
Lignite	16,400	17,351
Oil	43,920 - 46,365	44,002-46,259
Natural gas	42,110	39,394

Furthermore, to better depict mineral trade, Sankey diagrams have been used to represent the data. In such diagrams, the mineral resources that are extracted, imported, exported, recycled and consumed are represented by arrows proportional to their respective quantities, allowing the user to view with relative ease the differences in magnitudes. Another advantage is that with Sankey diagrams we can represent data both in tonnes and in exergy replacement costs so a direct comparative analysis of the data can be undertaken.

5.3. MAIN RESULTS

The Physical Geonomics model has been applied at the macro-scale using Spain, Europe (EU-28) and Colombia as case studies. The evolution over time of mineral extraction has been analyzed for Spain and Europe for the last decade, along with foreign dependency and mineral trade.

In the case of Spain, mineral extraction, imports and exports have been analyzed from 1995 to 2012. During that period, Spanish domestic extraction experienced a big increase related to the housing bubble but the most recent tendency is that extraction is decreasing both for non-fuel minerals and fossil fuels. In tonnes, imports represented approximately an average of 33% each year of the total inputs in Spain. When analyzing those results using exergy replacement costs, imports represent 73%, as the minerals that are imported are much more important from a scarcity point of view than those domestically extracted. While Spain is a major importer of gypsum, exports play a minor role and almost all of the materials that are imported and extracted are consumed within the borders of the country. A Sankey diagram has been used to represent mineral trade in Spain for the year 2011 both in tonnes and in exergy replacement costs (Figure 27).

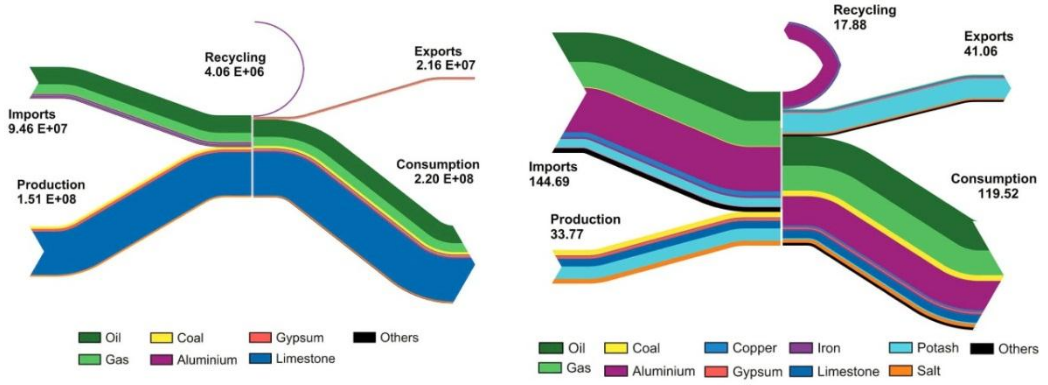

Figure 28. Sankey diagram representing Spanish mineral trade in tonnes (left; tonnes) and in exergy replacement costs (right; ERC) for the year 2011.

Despite the economic crisis that has been affecting the European Union and to policies related to resource management, which involves a general decrease in fossil fuel and non-fuel mineral consumption, the European Union is still fundamentally a consuming territory. Using exergy replacement costs instead of mass terms, the self-sufficiency of each country can be evaluated properly, as it places focus on the quality of the minerals (meaning critical minerals have a higher weight than limestone or industrial minerals that are more abundant). Almost all European countries have a high external dependence on natural resources supply, with consumption based more on importing than in exporting, generating an important trade deficit. Again, a Sankey diagram has been used to depict the EU-28 mineral trade for the year 2011, represented bot in tonnes and in exergy replacement costs (Figure 28).

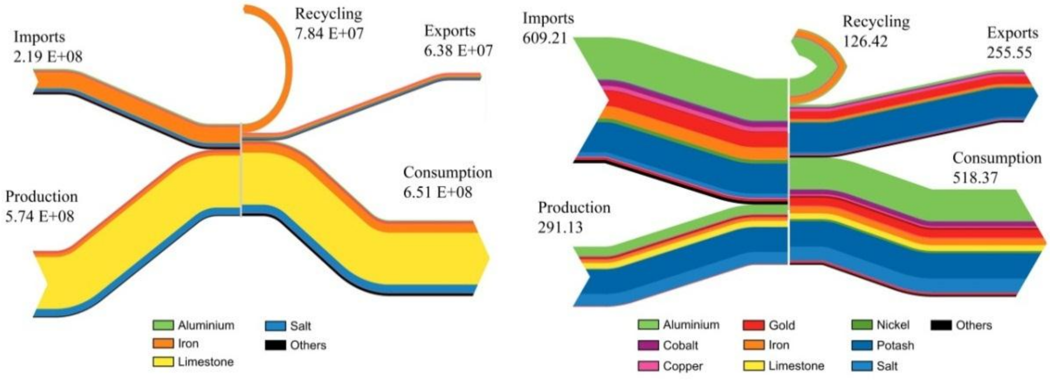

Figure 29. Sankey diagram representing European mineral trade in tonnes (left; tonnes) and in exergy replacement costs (right; ERC) for the year 2011.

Spain has been selected as the average European consuming country to carry out a comparative analysis with a mainly exporting country, such as Colombia. In addition to carry out an analysis of the mineral trade, the economic costs associated have also been studied, concluding that exporting countries, in this case Colombia, are underselling their resources. The contribution to the Colombian GDP of the mining sector in 2011 was $38 billion USD, if we take into account that to re-concentrate the minerals extracted Colombia would have lost an equivalent of $52-58 billion USD, clearly the monetary gain resulting from the extractive sector does not compensate the loss of mineral resources.

As demonstrated by all the case studies, a conventional material flow analysis does not truly reflect the real situation of mineral dispersion as all the minerals are considered at the same level. This problem can be overcome using exergy replacement costs, placing focus on the quality of those minerals.

5.4. PAPER III: AN EXERGOECOLOGICAL ANALYSIS OF THE MINERAL ECONOMY IN SPAIN.

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An exergoecological analysis of the mineral economy in Spain

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ABSTRACT

This paper shows how exergy can be used to assess the mineral balance of a country and at the same time assess its mineral resource sustainability. The advantage of using such an approach is that the quality of the resources is taken into account, as opposed to the conventional procedure that uses tonnage as a yardstick. The exergoecology method evaluates mineral resources as the exergy required to replace them from a complete dispersed state to the conditions they were originally found with the best available technologies. The country chosen as a case study is Spain and serves as a representative example of the mineral situation in Europe. The general trend observed is that imports are increasing and domestic production is decreasing. The minerals with higher exergy replacement costs are mainly those imported, including fossil fuels and scarce minerals. In 2005, the domestic production of minerals was higher than the imports but since imports were mainly of scarce minerals, the exergy loss associated with such imports was higher compared to domestic production. As it happens to most European nations, Spain is a very dependent country regarding the supply of fossil fuels but not as much in the case of non-fuel minerals.

1. Introduction

In the last two decades increased efforts in the compilation of material flows accounts in the European Union [1,2] and also in other countries of the world [3–6] are being made. Such accounts serve to analyze tendencies in material use and efficiency through different indicators. Material flow accounting and analysis has demonstrated to be a key tool to quantify and monitor human use of available natural resources.

Generally, comparative analysis between nations and specific analysis of single countries use aggregated indicators, taking into account biomass, agriculture, wood, food, animal stock, fossil fuels and minerals (industrial and construction minerals). However, while aggregated indicators can be used to highlight differences, it is also necessary to carry out a more disaggregated analysis to observe the impact of the different factors. Some studies are being conducted in other countries that contain more disaggregated data, such as those made in several European Countries and in Uzbekistan [7,8] and it is important to make further progress in this direction. In this paper we are going to focus our material flow analysis exclusively on mineral resources, including non-fuel minerals and fossil fuels, since its demand is growing exponentially as they are essential for the development of an economy.

Worthy of note is also the fact that conventional material flow analyses are usually carried out using tonnage as a yardstick. Alternatively, money is also frequently used. Nevertheless, both numeraires do not reflect the quality and scarcity of the resources used. The first one implies adding “apples” with “oranges”, whereas the second one is subject to monetary fluctuations alien to the physical reality.

The reality is that once used, minerals usually end up in landfills and get dispersed throughout the crust. Since the recovery of dispersed materials is according to the Second Law an extremely energy intensive activity, it is easier to increase extraction to meet the new raw material demand than to try to concentrate those dispersed minerals. As a result, mineral deposits become more and more depleted and energy and environmental costs are increasing. In just one century man has already depleted 26% of its world non-fuel mineral reserves [9] and this tendency is not likely to change in the near future. Accordingly, it is becoming increasingly important to improve the management of mineral resources to ensure future availability and also to have reliable and accurate data on material

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flows to evaluate the loss of mineral capital. Yet the indicators used for such an endeavor should reflect the fact that future generations will need to extract low-quality resources, since the low-hanging fruits have been already picked.

2. Methodology and data sources

In order to assess the mineral depletion and their associated costs the exergoecology method initially proposed by Valero in 1998 [10], is applied. Such method derives from a general theory developed some years before [11], and consists on the application of the exergy analysis to the evaluation of natural resources defined from a reference environment. The aim of this methodology is to assess the exergy costs that would be needed to replace the dispersed minerals back into their initial conditions of composition and concentration in which they were originally found. Since Nature has already concentrated those minerals into deposits, the energy needed to extract them is lower than if they were dispersed throughout the crust.

Evaluation of mineral resource depletion can be undertaken through LCA (Life Cycle Assessments) but the conventional approach, from cradle to grave, does not adequately reflect mineral dispersion. Accordingly, we propose to use a grave to cradle approach [12]. In our case the hypothetical grave is a depleted planet, called *Thanatia*, where all the minerals have been depleted and are dispersed and all fossil fuels have been burnt [13,14]. This then serves as a boundary limit and as a reference baseline to calculate the exergy and exergy replacement costs of any commodity. The former provides a minimum but absolute value. Yet it is very far removed from the value one would assign to minerals. Therefore, it is necessary to multiply such values by the so-called unit exergy costs, unique to each mineral (see Appendix, Table A.1). These unit exergy costs represent the relationship between the energy invested in the real obtaining process for mining and concentrating a mineral and the minimum energy that would be required if the process were reversible. It is a measure of irreversibility and it provides a rough idea of which minerals would be the most difficult to replace with current technology. With the unit exergy replacement costs we can estimate the exergy replacement costs for each substance. In the case of fossil fuels, since once they are consumed and burned they cannot be replaced, their exergy costs can be approximated to their high heating values. The complete methodology can be found fully developed in Ref. [15].

The relevance of conducting this analysis using exergy replacement costs instead of just tonnes can be seen in Fig. 1. Comparing the extraction of gypsum, potash and salt we can clearly see that the results expressed in tonnes and in exergy replacement costs vary considerably. These changes are related to the quality of the resources, scarcity and mining and processing energy. In this case, gypsum is the most extracted mineral but its unit exergy replacement costs is the lowest of them all (15.4, compared to the 1224.2 of potash or 44.1 of salt). The ultimate goal is to draw attention not only to the extraction of minerals but also put an emphasis on the quality of these resources.

Of all the countries of the European Union we are going to use Spain as an example of an extracting and importing country. Spain is representative for import rates across Europe, with average numbers in this category. The main differentiating factor is due to the production of industrial and construction minerals, for which Spain is above the European average.

To assess the mineral balance in Spain, data for domestic extraction, imports and exports for non-fuel minerals and fossil fuels for the period 1995–2011 have been compiled. The domestic extraction has been obtained from the annual reports of the Spanish service of mining statistics [16] that collects, among others, data about the amount of minerals in tonnes extracted in the country. Those data have been completed with several other statistics services, such as the ones provided by the United States Geological Service and the British Geological Survey. Even if there are numerous sources, available data are not always very accurate and sometimes the records are even incomplete and have serious information gaps. However, with all these records we can have an approximate idea of the Spanish mineral balance and the changes occurred over time. Information concerning imports has been obtained from the Spanish Chamber of Commerce, I.G.M.E. (Instituto Geológico y Minero de España) and from the Ministry of Industry, Energy and Tourism of Spain. Data from Datacomex for exports and imports, for non-fuel minerals and fossil fuels have been used (Foreign trade statistics of Spain). For natural gas and oil some years have been additionally compiled with the CORES statistics (Corporación de Reservas Estratégicas de Productos Petrolíferos). Gathering data for exports and imports has been particularly difficult in some cases since numerous sources did not consider the same factors and it differed considerably.

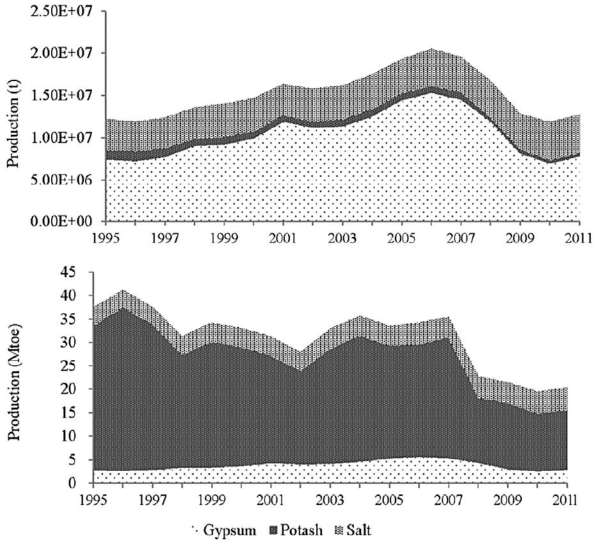

Fig. 1. Domestic extraction of several minerals represented in tonnes and in exergy replacement costs from 1995 to 2011 in Spain.

Since we rely on previous data of unit exergy costs, concentrating, smelting and refining exergies obtained in previous researches [17] we can only analyze approximately half of the mineral production in Spain. Therefore this work is only going to focus on the production, imports and exports of the following 29 substances: aluminum, antimony, bismuth, cadmium, chromium, cobalt, copper, fluorspar, gold, gypsum, iron ore, lead, limestone, lithium, manganese, mercury, molybdenum, nickel, phosphate rock, potash, salt, silicon, silver, tin, titanium, uranium, wolfram, zinc and zirconium. For simplification purposes it has been assumed that each substance is extracted only from one mineral ore. For fossil fuels, we are going to take into account natural gas, oil and coal (anthracite, bituminous coal, subbituminous coal and lignite).

In this paper we will apply the aforementioned methodology to assess the loss of mineral wealth caused by the DMC (domestic material consumption = production + imports − exports) of Spain for the years 1995–2011 for minerals and fossil fuels. We are also going to analyze the ratio of DE (domestic extraction) to DMC, i.e. the "self-sufficiency ratio", since it indicates the dependence of the physical economy on domestic raw material supply [18], and also the Imports/DMC ratio, that indicates the foreign dependency ratio.

3. Case study: Spain

The mining sector in Spain has historically been important for the economy. Throughout the years, many mines in Spain have closed due to the decreasing ore grade of metallic minerals, mineral depletion and also due to low profitability. At the beginning of the 20th century, mainly metallic minerals were extracted, such as copper, iron and lead. However, there has been a change in the tendency in the second half of the century, and the extraction of industrial minerals (construction and ornamental materials) increased significantly, a situation that is now starting to normalize due to the recent economic crisis. As it can be seen in Table 1, there has been a severe decrease in the number of mines extracting fossil fuels and metallic minerals between 1995 and 2010, 66% and 60% respectively. Regarding construction minerals and non-metallic minerals, there is an important increase, 11% from 2000 to 2007, closely related to the housing bubble [19].

With globalization, it has become cheaper and easier to simply import the minerals that are needed or directly to import the byproducts. Nowadays, only a limited number of mines are still in operation, being dedicated most of them to the extraction of industrial minerals such as limestone, gypsum and celestite. According to the latest report made by the United States Geological Survey (U.S.G.S.), in 2012 Spain was the third producer of gypsum at world level, after China and Iran, the fifth world producer of sand and gravel, and the sixth world producer of fluorspar, among others [20]. With the recent price increase of some metallic minerals, such as gold or wolfram, there are some companies promoting the reopening of several metallic mineral mines in the northern sector of the country since even if the ore grades are not very high, some of the mineral deposits are now considered economically profitable.

3.1. Extraction

Mineral resources are not equally nor homogeneously distributed throughout the Spanish territory since the concentration and location of the mineral deposits depends on the chemical and geological processes that have occurred over time.

In Fig. 2 we can see represented the data for domestic extraction, in tonnes, and exergy replacement costs, in Mtoe for the time period 1995–2011 for non-fuel minerals and for fossil fuels. A more detailed study on Spanish data series of domestic mineral extraction can be found in Ref. [21].

In this particular case the minerals that experienced a bigger increase in extraction were mainly gypsum and limestone, the latter being very important for building and infrastructure construction. Also this increase was related to the housing bubble. With the boom in the construction sector, extraction increased considerably and when the demand fell again due to the economic crisis the extraction also diminished. In general, non-fuel minerals extraction has been more dependent on the necessities of bulk material for the domestic market. However for the rest of the minerals, especially in the case the metallic minerals, the ore grades of the Spanish mines have been declining, many mines have closed and it has become easier to import them or directly import the byproducts.

Table 1
Evolution of the number of mines or mining groups by types of substances (1995–2010).

	1995	2000	2007	2010
Fuel minerals	135	84	62	46
Metallic minerals	15	10	2	6
Non-metallic minerals	190	185	114	192
Construction minerals	3158	3485	4303[a]	3.368[a]
Total	3498	3764	4181	3612

[a] Includes ornamental rocks [16].

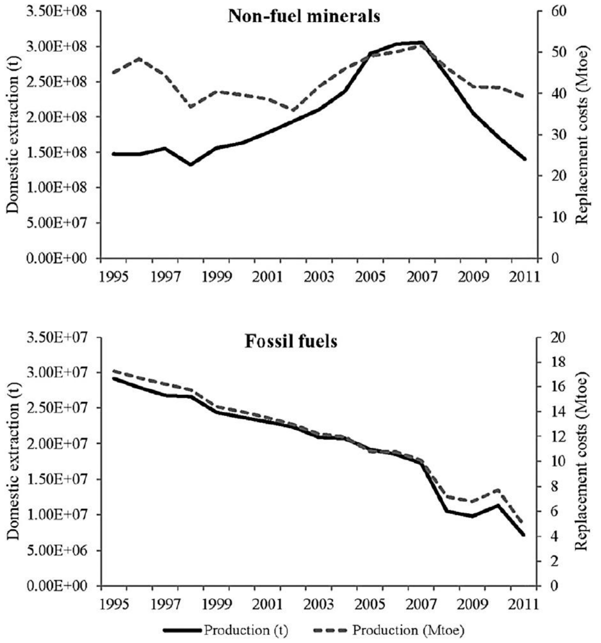

Fig. 2. Domestic extraction (in tonnes) and exergy replacement costs (in Mtoe) for non-fuel minerals and fossil fuels from 1995 to 2011 in Spain.

For fossil fuels we can see that there is a clear decrease tendency in domestic extraction. Though Spain has never been a major producer of fossil fuels, as of 2014, it has 530 million tonnes of reserves of coal, equivalent to 0.06% of the world reserves [22]. Coal is the main fossil fuel extracted in Spain, reserves and deposits are mainly concentrated in the NW and in the central-eastern zone, although there are small deposits scattered along the country. Generally the deposits are low quality and they are lignite-subbituminous rank [23]. Oil is extracted in the eastern and northwestern part of the territory, and also some offshore deposits have been discovered recently in the Canary Islands and in the Bay of Valencia. Even if Spain has some proven reserves of natural gas, compared to oil and coal, the extraction of natural gas can be considered almost irrelevant. This tendency of reducing the domestic extraction of fossil fuels does not imply a reduction of the consumption. With the current economic crisis, consumption of fossil fuels has in fact diminished, but the principal explanation for this general decrease is that Spain extracts less. This is caused not only by the environmental policies and the elimination of the subsidies, but also due to the geological conditions and structural complexity of the deposits, making them economically unprofitable for most cases. This results in part in an increase of imports, shifting the environmental burden associated and the loss of resources to other countries.

In the case of non-fuel minerals the general tendency of data expressed in tonnes and in exergy replacement costs is more or less equivalent, except for the years 2004–2007. In this period, the changes in data expressed in exergy terms are less abrupt. Indeed, even if domestic extraction increases, the associated exergy replacement costs remains constant or decrease, although it would be expected to increase as well. This is the result of the change in the domestic extracted minerals; the increase corresponds to lower quality minerals (i.e. that have lower unit exergy replacement costs).

In the case of fossil fuels, as coal was predominantly extracted, both the data in tonnes and in exergy terms follow the same trend and are almost identical. This is because, as explained before, the exergy of fossil fuels is calculated by multiplying the tonnage by a factor close to its HHV (High Heating Values). In 2008 we can see a sudden fall in the extraction, caused by the closing of the As Pontes brown coal mine in 2007.

As we can see, in both cases, the current tendency is that domestic extraction is gradually decreasing. In the case of non-fuel minerals, this decrease is caused by the decreasing ore grades and changes in the necessities of bulk materials, we have to consider that extraction of construction minerals has reached 1995 levels. Nowadays the domestic mineral extraction is mainly based on industrial minerals. Fossil fuel extraction has decreased continuously over time, as the quality of Spanish coal is not optimal. Some deposits have high sulfur content and other impurities [23] and consequently the high heating values are very low. Another relevant reason for this decrease is that it is easier and cheaper to directly import fossil fuels and rely on other countries for the supply that produce them internally.

3.2. Imports and exports

3.2.1. Imports

Spain, as it happens to the rest of Europe, has not enough mines to be a self-sufficient country for most commodities. It doesn't have deposits of many of the considered critical raw materials for the European Union [24] and it must rely on imports to be able to cover the internal needs.

In the case of non-fuel minerals (Fig. 3), even if the tonnes imported are far less than the tonnes extracted, the exergy replacements costs for imports are higher than those for extraction. As explained before, this is the direct consequence of importing minerals with higher unit exergy costs (higher quality resources), such as aluminum or copper, while domestic extraction focuses on limestone and gypsum. Minerals with lower unit exergy costs, such as bulk construction minerals, are hardly traded due to its local abundance and lower prices. We can also see that in 2008–2009 there is an important decrease that slightly recovers in the later years. This is mainly caused by the economic crisis and the overall decline of imports. This is not reflected so dramatically in terms of exergy replacement costs since imports of minerals with higher exergy replacement costs do not decrease as much as imports of minerals with lower ones.

As shown by these results, there is a reversed importance of exergy loss and tonnes, which is a direct consequence on the quality of the resources (the amount of energy needed for mining and also on the ore grade of the mines). For example, considering the total inputs (production and imports), in 2005 the domestic production of minerals (71.2%) was higher than the imports (28.8%) but since imports were mainly of scarce minerals, the exergy loss associated with such imports was higher (73.6%) compared to the one associated to domestic production (26.4%).

In the case of fossil fuel imports we can see that they have gradually increased, experiencing some variations over time. If we compare these imports with the domestic extraction we can see that it is roughly between 5 and 15 times higher in terms of exergy replacement costs depending on the year under consideration. In recent years, from 2008 onwards, there has been a decrease of imports related to the economic crisis that is still affecting the country, reaching 1998 import levels of 2011.

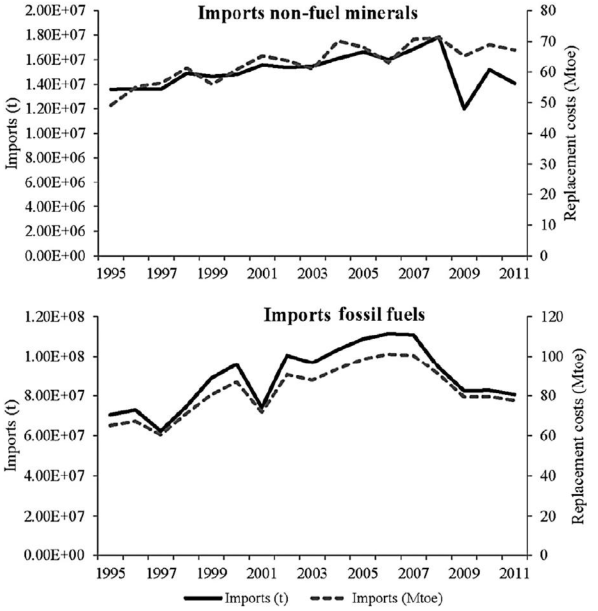

Fig. 3. Imports (in tonnes) and exergy replacement costs (in Mtoe) for non-fuel minerals and fossil fuels from 1995 to 2011 in Spain.

As it can be seen, Spain is a very dependent country in the case of fossil fuels. In 2009, the degree for oil self-sufficiency in Spain was 0.18% and for natural gas it was 0.04% [25]. The energy dependence or vulnerability to energy price shocks or energy supply disruptions is something vital for economies, since energy is a key variable for growth and competitiveness. Between 2006 and 2010 Spain had an average total import dependency of 80%, being the EU average 54%. Moreover, the gas and oil import dependency was 100% [26].

3.2.2. Exports

In comparison with domestic extraction and imports, exports are almost irrelevant. Exports are almost forty times lower than imports, but still it is interesting to see the changes during the considered period due to their importance they have in the economy (Fig. 4). During those years, the minerals exported were mainly aluminum, copper, gypsum, feldspar, potash, salt and zinc. Between 1995 and 2011, gypsum exports have always represented between 41 and 67% of the total exports, being one of the most important minerals for the Spanish economy. In 2011, 46.2% of the total mineral exports corresponded to gypsum, 17.2% to salt, 10.6% to copper, 9.1% to potash and 6.9 to zinc, the remaining 10% corresponded to other minerals.

The exports expressed in tonnes and in exergy replacement costs follow the same trend until 2004, where exergy replacement costs decrease dramatically. This drastic change is produced by the decrease of potash exports. Due to the elevated unit exergy replacement costs of potash, a small increase or decrease in tonnes can represent a significant change in exergy replacement costs terms. From 2004 to 2009 the exports were almost halved and it is not until 2010 when the previous exports levels were regained again.

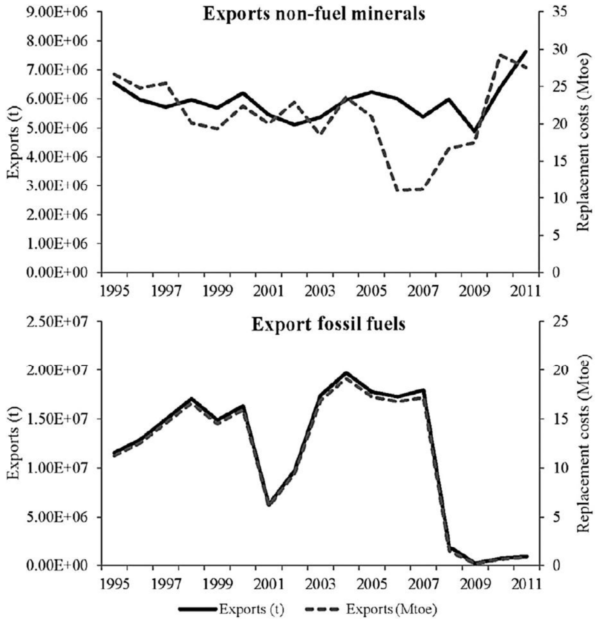

Fig. 4. Exports (in tonnes) and exergy replacement costs (in Mtoe) for non-fuel minerals and fossil fuels from 1995 to 2011 in Spain.

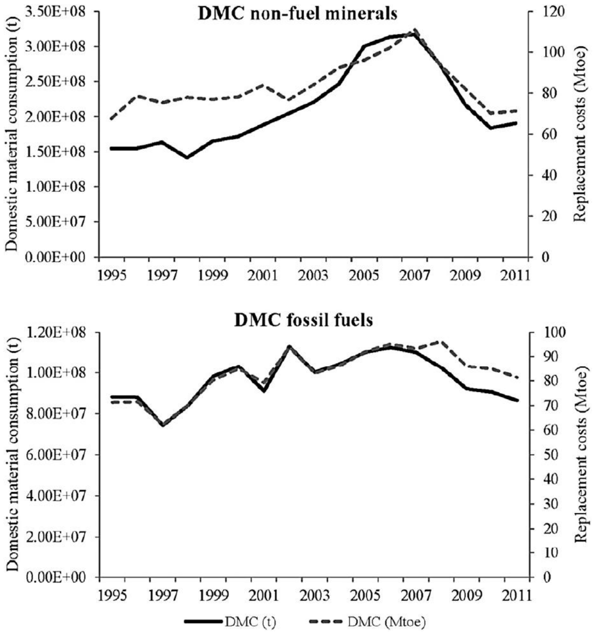

Fig. 5. Domestic material consumption (in tonnes) and exergy replacement costs (in Mtoe) for non-fuel minerals and fossil fuels from 1995 to 2011 in Spain.

Fossil fuels exports are very low compared to imports, from 6 to 10 times lower, and are quite similar to domestic extraction in general terms. In 2001–2002 the total amount of exported fossil fuels decreased considerably as oil product exports were almost halved in that period of time.

3.3. Domestic material consumption

With the DMC over time we are analyzing the evolution of the annual amount of the material extracted, plus all the imports minus exports (Fig. 5).

In the case of non-fuel minerals we can see that the DMC in tonnes does not exactly follow the same tendency as exergy replacement costs since from 1995 to 2004 the latter has a less pronounced slope. Minerals that are imported and a small amount of those that are extracted have higher exergy replacement costs, since they are usually scarcer minerals. The impact on the Spanish natural resource depletion is higher than expected if we look at the exergy loss than if we were just taking into consideration this loss in mass terms. In both graphics we can also see the influence of the economic crisis that started in 2008, where an important decrease of imports and domestic extraction took place.

We can also analyze the ratio of DE or production to DMC in tonnes. As stated before, this ratio indicates the self-sufficiency on domestic raw material supply. We can see the DE/DMC ratio for non-fuel minerals and fossil fuels, with the results expressed in tonnes, in Fig. 6.

In the case of non-fuel minerals, the DE/DMC ratio in tonnes varies from 0.92 to 0.96, meaning that in the case of the 29 minerals studied in this paper, Spain is not very dependent on other countries. It should be taken into account that the domestic extraction is mainly based on industrial minerals such as limestone, gypsum and potash. Performing a global analysis of the data, other minerals remain masked, and the dependence of these other substances, or others not included in this study, could be significant. The ratio in exergy replacement costs varies from 0.42 to 0.68, meaning that Spain is more dependent than it seemed at first.

In the case of fossil fuels we can observe that the DE/DMC ratio in tonnes varies from 0.09 to 0.41 (from 0.06 to 0.26 in exergy replacement costs) and it is clear that in this ratio is continuously decreasing over time. As we previously stated, Spanish supply for fossil fuels essentially depends on imports so it can be considered as an almost entirely dependent country. The exergy loss associated with this dependency falls in other countries, such as Iran, Russia and Libya, which is where the fossil fuel imports mainly come from Ref. [25].

With these results we can see that the tonnage indicator is not adequate to evaluate the quality of the resources and it does not reflect the real situation of external dependency.

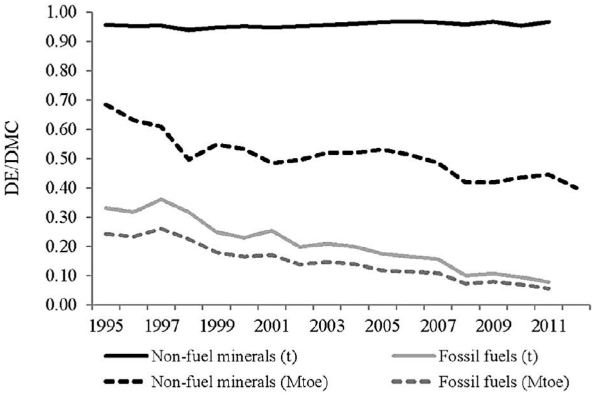

Fig. 6. Ratio of domestic extraction to domestic material consumption expressed in tonnes (t) and in exergy replacement costs (Mtoe) for non-fuel minerals and fossil fuels from 1995 to 2011 in Spain.

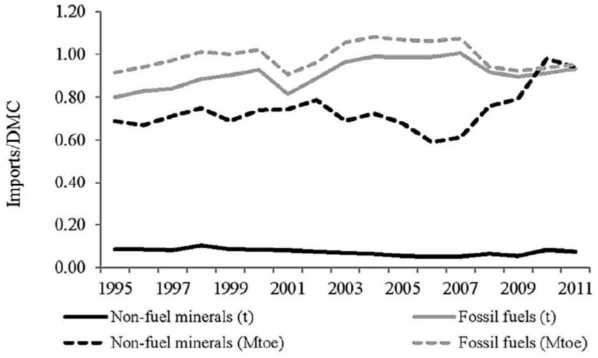

Fig. 7. Ratio of imports to domestic material consumption expressed in tonnes (t) and in exergy replacement costs (Mtoe) for non-fuel minerals and fossil fuels from 1995 to 2011 in Spain.

Considering the ratio Imports/DMC (Fig. 7), we can see the foreign dependency ratio. In the case of non-fuel minerals, if we observe the results in tonnes, it seems that they hardly traded (from 0.05 to 0.10), but in exergy replacement costs the importance of imports is better reflected (from 0.59 to 0.98). Again we see that Spain is a very dependent country regarding fossil fuels imports, since trade is fundamental in this case to support the economy, with ratio values next to 1 and sometimes even higher.

4. Conclusions

Developed countries are increasingly dependent on material and energy resources and in many cases the domestic production is not enough to meet the demand. This is because the geology of each region is determinant since minerals are formed under specific natural conditions and are concentrated in deposits that are not equally distributed around the Earth. This unequal distribution of the resources triggers the importations and exportations of mineral resources and raw materials. This generates a material flow that produces a shifting in the environmental burden to the exporting nations, which are usually non-developed countries with less restrictive environmental laws that create a greater environmental impact.

Analysis of natural resource accounting and material flow usually are carried out with the total amount of extracted tonnes instead of taking into account the scarcity of each of the materials that are being studied.

With exergy analysis we can infer that the quality of the resources is a critical parameter. For this reason the production of some minerals, such as copper or aluminum, cannot be compared with that of limestone or gypsum in mass terms. Using the exergoecology method, we have assessed the exergy costs that would be needed to replace the dispersed minerals back into their initial conditions of composition and concentration in which they were originally found. With this methodology we can obtain more realistic data for the loss of the natural capital of a country.

For this purpose, we have compiled data of domestic production, imports and exports for Spain from 1995 to 2011, a country that represents average European importing values. With the analysis of these exergy replacement costs we have studied the Spanish mineral balance and have also assessed its mineral resource sustainability and dependency.

Results show that domestic extraction of non-fuel minerals increased until 2008, when the economic crisis started. Contrarily, fossil fuel extraction has always been decreasing due to the depletion of reserves and low profitability. Equally, imports for non-fuel minerals and fossil fuels have increased over time, though we can also see the influence of the economic crisis. In this case, scarce minerals rather than industrial minerals are being imported. In the case of exports, gypsum has always been one of the main industrial minerals exported and fossil fuel exports can be considered almost negligible.

As we can see with the DE/DMC ratio, expressed in exergy replacement costs, Spain is a very dependent country regarding the supply of fossil fuels, with ratios continually decreasing from 0.26 to 0.06. Even if Spain has some internal production, the exergy loss associated to fossil fuel extraction is being transferred to other countries. In the case of non-fuel minerals, with ratios ranging from 0.42 to 0.68, we can say that Spanish supply, specially the supply of industrial minerals, depends less on other countries.

With natural resource accounting, particularly with the analysis in exergy replacement costs, we cannot only see how many resources we have extracted or dispersed but also evaluate the quality and scarcity of those resources. Current available data, whether from the government agencies or the mining companies, are sometimes incomplete and they do not fully reflect the situation. Since the Earth is not an infinite reservoir, more efforts should be undertaken to improve these databases.

Acknowledgments

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Appendix A

Table A.1. Exergy replacement costs of the 29 non-fuel minerals. Values are expressed in GJ/ton of substance.

Substance	Mineral ore	Unit exergy replacement costs	Mining and concentration energy	Smelting and refining energy
Aluminum	Gibbsite	627.3	10.55	23.87
Antimony	Stibnite	474.5	1.4	12.0
Bismuth	Bismuthinite	489.2	3.6	52.8
Cadmium	Greenockite	5898.4	263.9	278.5
Chromium	Chromite	4.5	0.1	36.3
Cobalt	Linaeite	10,871.9	9.2	129.0
Copper	Chalcopyrite	110.4	28.8	21.4
Fluorspar	Fluorite	182.7	1.5	0.0
Gold	Native gold	583,668.4	107,751.8	0.0
Gypsum	Gypsum	15.4	0.2	0.0
Iron	Hematite	17.8	0.7	13.4
Lead	Galena	36.6	0.9	3.3
Limestone	Calcite	2.6	0.4	5.8
Lithium	Li in brines	545.8	12.5	420.0
Manganese	Pyrolusite	15.6	0.2	57.4
Mercury	Cinnabar	28,298.0	157.0	252.0
Molybdenum	Molybdenite	907.9	136.0	12.0
Nickel	Pentlandite	761.0	15.5	100.0
Phosphate rock	Fluorapatite	0.4	0.3	4.6
Potash	Sylvite	1224.2	3.1	0.0
Silicon	Quartz	0.7	0.7	76.0
Silver	Argentite	7371.4	1281.4	284.8
Sodium	Halite	44.1	3.3	39.6
Tin	Cassiterite	426.4	15.2	11.4
Titanium	Ilmenite	4.5	7.2	128.1
Uranium	Uraninite	901.4	188.8	0.0
Wolfram	Scheelite	7429.3	213.0	144.0
Zinc	Sphalerite	24.8	1.5	40.4
Zirconium	Zircon	654.4	738.5	633.0

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5.5. PAPER IV: MATERIAL FLOW ANALYSIS FOR EUROPE. AN EXERGOECOLOGICAL APPROACH.

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Material flow analysis for Europe: An exergoecological approach

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A B S T R A C T

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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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

Table 1
Exergy replacement costs (ERC) of selected minerals (Valero and Valero, 2014).

Substance	Mineral ore	ERC (GJ/tonne)	Substance	Mineral ore	ERC (GJ/tonne)
Aluminium	Gibbsite	627.3	Magnesium	Magnesite	–
Antimony	Stibnite	474.5	Manganese	Pyrolusite	15.6
Arsenic	Arsenopyrite	399.8	Mercury	Cinnabar	28,298.0
Barium	Barite	–	Molybdenum	Molybdenite	907.9
Bismuth	Bismuthinite	489.2	Nickel	Pentlandite	761.0
Boron	Kernite	–	PGM	Cooperite	–
Cadmium	Greenockite	5898.4	Phosphate rock	Fluorapatite	0.4
Chromium	Chromite	4.5	Potassium	Sylvite	1224.2
Cobalt	Linaeite	10,871.9	Selenium	Se in Cu ores	–
Copper	Chalcopyrite	110.4	Silicon	Quartz	0.7
Feldspar	Orthoclase	–	Silver	Argentite	7371.4
Fluorspar	Fluorite	182.7	Sodium	Halite	44.1
Gold	Native gold	583,668.4	Tantalum	Tantalite	482,827.9
Graphite	Graphite	–	Tin	Cassiterite	426.4
Gypsum	Gypsum	15.4	Titanium	Ilmenite	4.5
Indium	In in Zn ores	–	Uranium	Uraninite	901.4
Iron ore	Hematite	17.8	Vanadium	V in other ores	1055.3
Lead	Galena	36.6	Wolfram	Scheelite	7429.3
Limestone	Calcite	2.6	Zinc	Sphalerite	24.8
Lithium	Li in brines	545.8	Zirconium	Zircon	654.4

extraction of non-fuel minerals decreased almost by 40%. This crisis mainly affected the construction mineral sector, especially limestone extraction. This alteration seems tightly associated with the bursting of the housing bubble and financial crisis that took place in several European countries during the 2007–2009 period (European Commission, 2009).

As for fossil fuels, domestic extraction is clearly decreasing. In the last 18 years, the domestic extraction of fossil fuels has diminished approximately by 28%. Coal remained the main fossil fuel extracted, accounting for 66.7% of the total production as an average, while natural gas and oil accounted for 17.9% and 15.4%, respectively.

Fig. 2 shows a general overview of mineral trade from 1995 to 2012 in the EU-28. Whilst non-fuel mineral imports and exports remain roughly constant over time, fossil fuel imports present more fluctuations. Although the total amount of imported fossil fuels is generally increasing, several drastic changes can be appreciated. Between 2003 and 2004 the total amount of fossil fuels imported increased by 27% and from 2007 onwards there has been a sharp decrease corresponding to the financial crisis. Yet in the latter years it seems that the tendency is recovering certain stability.

If we take into account non-fuel minerals and fossil fuels, between the years 2001 and 2011, the total amount of imports in Europe increased by around 35% while the total domestic extraction decreased almost 6% during that same period.

Material trade deficit (exports minus imports) was analyzed for the selected group of non-fuel minerals (Fig. 3). As it can be seen, imports exceed exports during the whole time period, generating a substantial material trade deficit. The maximum amount of imported non-fuel minerals was 257 million tonnes in 2007 and the maximum exports were 63.3 million tonnes in 2001. On average, exports were equivalent to 23.74% of the imports and the maximum deficit, 210 million tonnes, occurred in 1998.

4. Comparative analysis between 2001 and 2011

Fig. 4 represents the European mineral balance for the years 2001 and 2011 expressed in tonnes.

The general behaviour that can be inferred is that European member states mainly imported oil, coal, natural gas and iron. Domestic production was in turn dominated also by the three main fossil fuels, but also by limestone and potash. The rest of the minerals presented in Table 1 were also taken into account for this study but their trade quantities are so low in mass units that they cannot be seen in this diagram and are represented as "others".

As stated by other authors, the import dependency for EU countries is very high and this tendency over time can be corroborated with the data presented in this paper. In 2001 approximately half of the input materials (50.7%) came from other countries and in 2011 this ratio was 45.8%. It is also noteworthy that all of the imported and produced minerals ended up being consumed within the

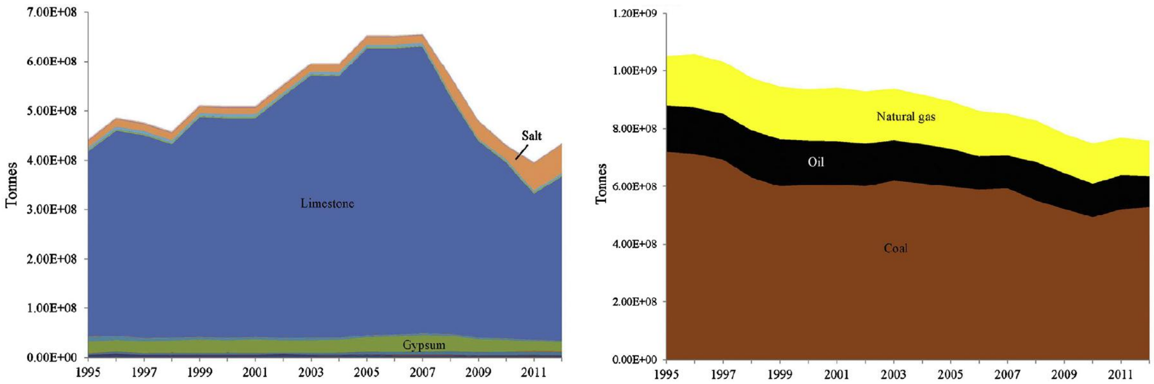

Fig. 1. Non-fuel mineral production (left) and fossil fuel production (right) in EU-28 from 1995 to 2012.

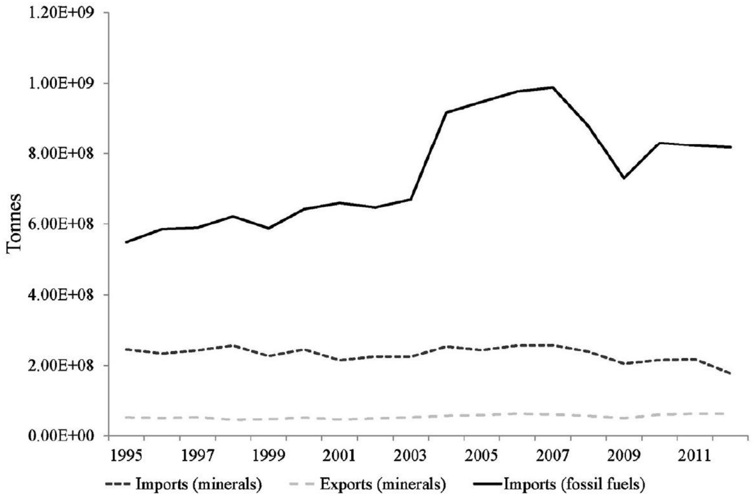

Fig. 2. Tonnes of fossil fuels imported and tonnes of non-fuel minerals imported and exported in Europe from 1995 to 2012.

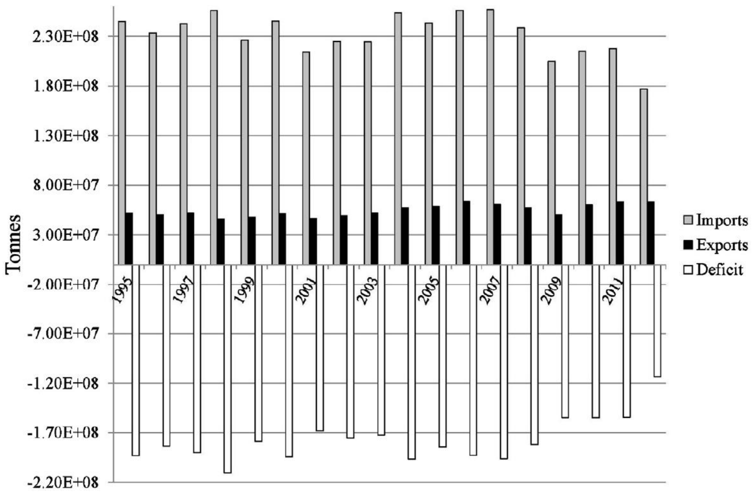

Fig. 3. Physical imports, exports and material trade deficit (exports–imports) for the EU-28 from 1995 to 2012.

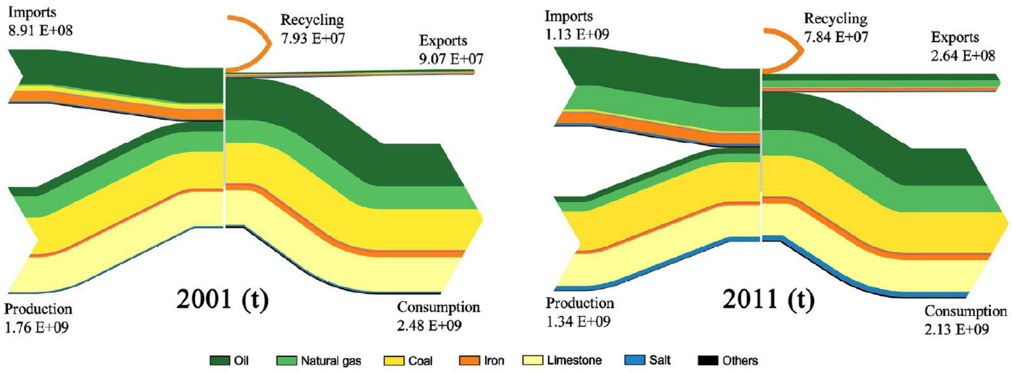

Fig. 4. Sankey diagram for the European mineral balance for 2001 and 2011. Data are expressed in tonnes (t).
Source: British Geological Survey (2014).

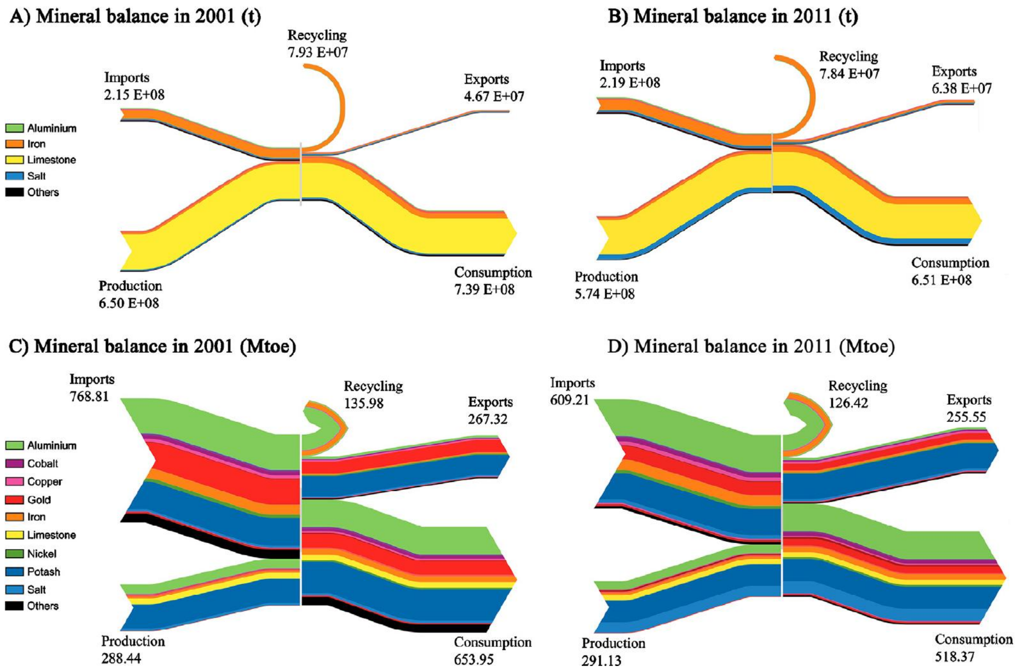

Fig. 5. Sankey diagrams for the EU-28 mineral balance for 2001 and 2011 for non-fuel minerals. Data are expressed in tones (A, B) (t) and in exergy replacement costs (C, D) (Mtoe).

European member states borders, stressing that, at least regarding these substances, Europe is an extremely dependent economy.

One alternative for reducing imports lies in recycling, saving both consumption of energy and natural resources. Although some countries have higher recycling rates than the average, Europe is “wasting” vast quantities of valuable resources and sending them to landfills. Owing to low efficiencies in the processing and collection of metal-bearing products that are discarded, and because primary materials are often abundant, the end-of-life recycling rates are still very low although the European policy efforts in this field are slowly being noticed in the recycling statistics. In 2001, 2.9% of the total input materials (domestic production plus imports) were recycled. This percentage increased to 3.2% in 2011. That said, recycling targets are still based on tonnage rather than focusing on critical raw materials.

As for exports, they only represented 3.4% and 10.7% respectively of the output materials. On the other hand, internal consumption in the EU-28 accounted for 93.6% and 86.2% respectively. These data can help emphasizing that Europe is a continent mainly based on consumption.

In Fig. 5 data from fossil fuel trade have been removed so that we can concentrate on non-fuel minerals. Comparing mineral trade data in tonnes between the years 2001 and 2011, it can be observed that the situation is roughly the same with some exceptions. Accordingly, in 2011 the amount of salt traded was higher, enough to be visible in Fig. 5B, when compared to the amount traded in 2001. The amount of imported and recycled minerals remained constant while production decreased; exports were slightly higher in 2011.

If we compare the mineral trade in mass terms and in ERC, we can clearly see that the minerals have different weight depending on which factor is being considered. With data in tonnes we can only display quantities, which can give a general idea of the mineral trade, but at the same time it is also giving biased information as many minerals are not extracted in sufficient quantity to be represented. With ERC we can evaluate the quality of those minerals, bringing out those that are scarcer or less concentrated in the crust For example, limestone and iron were the most traded minerals in weight in 2011, accounting for 77.1% of the total input materials. If we express the same data in ERC, limestone and iron only represent 10.8%. As for other minerals, the amount of gold imported in 2011 seemed negligible when using mass units, but when using ERC gold represents almost 12% of the total imports.

In 2011 consumption played an important role both in tonnes and in ERC, representing respectively 86.2% and 74.5% of the total outputs. What draws our attention is that in tonnes, the percentage corresponding to production (54.2%) is higher than the one corresponding to imports (45.8%), but in the case of ERC we have the opposite situation (34.1% and 65.9%). The fact that consumption is always very important is not surprising, what is noteworthy is the reversed importance of production and imports depending on how the resources are being evaluated. If we only add tonnes of minerals, the production is higher than imports but if we take into account the quality of those minerals it is the imports that become more relevant since Europe imports scarcer and more valuable minerals (from a physical point of view) than those that are domestically extracted.

In 2014 the European Commission updated the list of critical minerals for the European Union (European Commission, 2014), of which the vast majority has been taken into account in this study. For this reason comparing the results in mass terms and in ERC becomes fundamental to analyze the mineral trade since these critical and scarcer minerals are better represented with the latter analysis. When evaluating the mineral depletion caused by trade in 2011 in the EU-28 in mass terms and in ERC terms, we can see for instance that the internal production of 10 of the 20 minerals considered critical by the EC in its 2014 report, accounted for 0.88% of the total production expressed in tonnes and 3.19% when expressed in ERC.

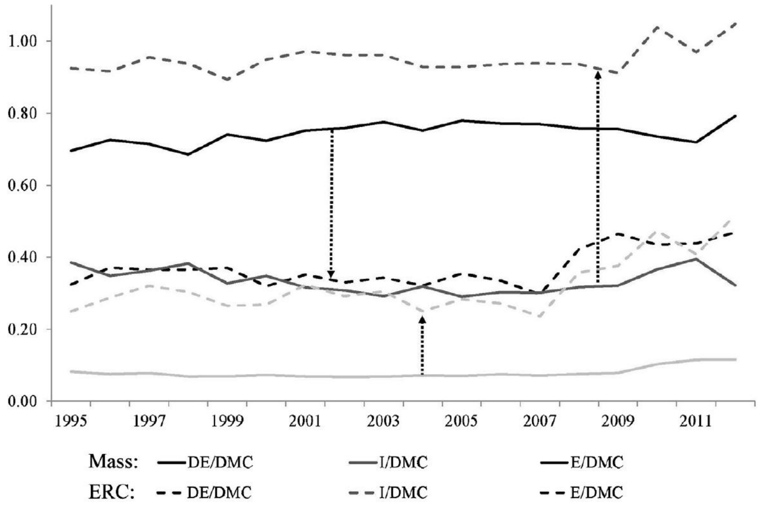

Fig. 6. Self-sufficiency (DE/DMC) and foreign dependency indicators (E/DMC and I/DMC) for non-fuel minerals from 1995 to 2011 for EU-28.

With all the information presented above, it can be seen that the results in tonnes cannot precisely reflect the real situation. Therefore using exergy replacement costs can help to better reflect the use of critical minerals.

5. Mineral dependency in the EU-28

5.1. General situation

With total data of domestic extraction, imports and exports we can calculate a number of ratios to evaluate several factors of dependency.

The material flow indicator Domestic Material Consumption (DMC) measures the amount of raw materials extracted plus all physical imports minus all physical exports. Proceeding from this indicator, we can also obtain the ratio Domestic Extraction to Domestic Material Consumption (DE/DMC), which is an indication of the self-sufficiency ratio. We can also obtain the imports to DMC (I/DMC) and exports to DMC (E/DMC) ratios used to evaluate the foreign dependency and trade intensity of the EU-28. In Fig. 6 we can see the evolution of the aforementioned indicators for non-fuel minerals. The self-sufficiency ratio (DE/DMC) varies between 0.69 and 0.79 when data are expressed in mass terms and between 0.30 and 0.47 when data are expressed in ERC terms. This contrast is caused by the weight in tonnes of construction and bulk minerals, creating a false appearance of self-sufficiency.

As for the foreign dependency, in the case of the indicator I/DMC ranges between 0.29 and 0.39 in mass terms and between 0.89 and 1.05 in ERC terms. Again mineral quality takes over quantity in this second case, and this indicator can help to highlight that Europe is more dependent than it appears regarding imports of scarcer minerals. In the case of exports, E/DMC indicator, the main exported substances are aluminium, gold, salt and potash, all minerals with high ERC, which is why the values of the indicator are higher when expressed in those terms than when using mass units.

5.2. Mineral dependency in 2011

Table 2 shows the ratios obtained for the case of non-fuel minerals and fossil fuels for the year 2011. In this first case the DE/DMC ratio is 0.79 with data expressed in tonnes and 0.45 with data expressed in ERC. If we only used the first data to evaluate external dependency on non-fuel minerals, we could conclude that EU-28 is not very dependent on external supply since the indicator has a relatively high value. However, there is a difference of 34% between the two DE/DMC values obtained with the two calculation methods. Again, this is mainly due to the relevance in mass terms of the limestone extracted in the EU-28, which was 295 million tonnes, 74.5% of the total extraction of minerals in that year. Since construction materials are hardly traded due to their lower price and abundance, putting them at the same level as scarcer minerals does not seem appropriate. Using ERC we have a better approximation of the indicator DE/DMC which shows the low self-sufficiency.

For imports and exports, I/DMC and E/DMC, the opposite situation occurs. These two ratios are significantly higher when data are expressed in ERC terms than in tonnes, which reflect that EU-28 is also dependent on foreign trade for non-fuel mineral supply.

As for the ratios obtained for the case of fossil fuels, 0.52 and 0.41, they are not so distant from each other when expressed in mass or in ERC terms. The dependency on imports becomes clear when observing the I/DMC ratio, 0.62 when using data in tonnes and 0.76 when using ERC. These results point out that as it happens with non-fuel minerals, Europe is also very dependent on fossil fuel supply.

Values of production, imports, exports and for the aforementioned indicators of all EU-28 member states can be found in Table 3. Data are arranged in descending order by total domestic production of non-fuel minerals. The first five countries of the table account for more than 64% of the total production expressed in ERC. In 2011 Germany was the main producer, importer and exporter country in ERC terms, which seems logical being a leader in several industrial and technological sectors as well as one of the largest economies by nominal GDP (United Nations, 2013). According to data in Table 3, the country that had a highest self-sufficiency degree in 2011 was Cyprus, which can be explained by the low rate of imports and

Table 2
Ratio between domestic extraction and domestic material consumption (DE/DMC), imports/DMC and exports/DMC for EU-28 for the year 2011 for non-fuel minerals and fossil fuels.

	DE/DMC	I/DMC	E/DMC
Non-fuel minerals			
Mass	0.79	0.30	0.09
ERC	0.45	0.94	0.40
Fossil fuels			
Mass	0.52	0.62	0.13
ERC	0.41	0.76	0.17

Table 3
Values for production, imports, exports, DMC and selected indicators for EU-28 expressed in exergy replacement costs for the year 2011 for non-fuel minerals plus fossil fuels.

	Prod (Mtoe)	Imports (Mtoe)	Exports (Mtoe)	DMC (Mtoe)	DE/DMC	I/DMC	E/DMC
Germany	215.98	289.49	129.96	375.51	0.58	0.77	0.35
United Kingdom	121.36	136.83	82.77	175.42	0.69	0.78	0.47
Poland	91.36	27.46	2.79	116.02	0.79	0.24	0.02
Netherlands	60.34	110.39	12.85	157.88	0.38	0.70	0.08
Greece	59.77	23.58	8.04	75.30	0.79	0.31	0.11
Czech Republic	34.99	27.19	4.03	58.14	0.60	0.47	0.07
Spain	33.77	144.69	109.73	71.40	0.49	2.11	1.60
Romania	29.71	30.35	1.19	58.86	0.50	0.52	0.02
Italy	28.41	145.21	7.75	165.87	0.17	0.88	0.05
Bulgaria	19.11	9.31	0.69	27.73	0.69	0.34	0.03
Denmark	14.86	6.32	8.19	13.00	1.14	0.49	0.63
France	12.68	165.92	13.78	164.82	0.08	1.01	0.08
Sweden	11.56	25.27	12.98	23.85	0.48	1.06	0.54
Austria	5.99	33.97	5.71	34.25	0.17	0.99	0.17
Hungary	4.17	8.62	0.40	12.39	0.34	0.70	0.03
Portugal	3.58	15.89	1.53	17.94	0.20	0.89	0.09
Croatia	2.46	8.50	0.25	10.71	0.23	0.79	0.02
Estonia	2.12	0.75	0.52	2.36	0.90	0.32	0.22
Slovenia	1.88	2.19	0.41	3.66	0.51	0.60	0.11
Slovakia	1.35	19.26	2.05	18.55	0.07	1.04	0.11
Belgium & Luxembourg	0.94	102.88	35.13	68.68	0.01	1.50	0.51
Finland	0.74	51.94	5.70	46.98	0.02	1.11	0.12
Ireland	0.60	73.31	0.72	73.19	0.01	1.00	0.01
Malta	0.46	0.05	0.00	0.52	0.90	0.10	0.00
Lithuania	0.18	13.25	0.48	12.96	0.01	1.02	0.04
Cyprus	0.13	0.03	0.13	0.03	4.30	0.81	4.11
Latvia	0.08	1.40	0.22	1.26	0.06	1.11	0.17
Average EU-28	27.09	52.64	16.00	63.74	0.54	0.77	0.35

production. Of all the European countries, nine have a I/DMC ratio equal or greater than 1, these countries more or less correspond to the ones that have lower domestic extraction, so it seems logical that they must heavily rely on imports.

In Europe there is a large variation between each of the member states regarding size, GDP, economic growth, geology, characteristics of the mining industry, etc. This is why the average ratios obtained must be taken only as a reference. The average self-sufficiency (0.54) and the elevated import dependency (0.77) make clear that Europe must rely on other regions to cover its own needs.

6. Conclusions

In this paper the exergoecology methodology has been applied to undertake a material flow analysis for Europe from 1995 to 2012.

For the period under consideration, domestic extraction in EU-28 has been decreasing continuously. Especially notable is the case of fossil fuels, which decreased 28% between 1995 and 2012. This decrease can be attributed to emphasis on resource management and to implemented resource efficiency policies as well as to the economic crisis that has been affecting the member states over the last years.

Yet as demonstrated by the data presented in this paper, a conventional material flow analysis does not truly reflect the real situation of mineral dispersion, as all the minerals, regardless their quality, are considered at the same level. If we only used mass terms, EU-28 could be almost considered as a self-sufficient territory regarding non-fuel mineral supply, as the domestic extraction to domestic material consumption ratio (DE/DMC) in 2011 was 0.79, but this does not truly reflect the real situation. This is because critical minerals from a physical point of view are given a lesser importance in the overall analysis. As presented in this paper, this problem can be overcome using exergy replacement costs, placing focus on quality minerals.

Using exergy replacement costs we can see that the value of that same DE/DMC ratio would be 0.45, placing more emphasis on the external dependence of EU-28 regarding non-fuel minerals. For example, European Countries imported in 2011 an average of 52.64 Mtoe between fossil fuels and non-fuel minerals, a significant number if we take into account that the DMC for that same year was 63.83 Mtoe in ERC terms. Considering the elevated trade deficit, the average self-sufficiency ratio in the EU-28 (0.54) and the import dependency (0.77), it can be stated that the member states of the European Union heavily rely on imports and consumption of high valuable minerals rather than on domestic production or exports.

Therefore, using only mass terms to evaluate mineral capital generates incomplete results that end up affecting resource efficiency policies. For instance, recent initiatives are promoting raw material strategies in the European Union, increasing recycling rates and creating synergies between industries. Such is the case of the Waste Electrical & Electronic Equipment (WEEE) Directive (European Parliament and Council, 2012), that encourages creation of collection schemes, proper treatment, recovery and restriction of the use of certain hazardous substances. Still, there is a long way to go when raw material recycling is concerned. Policies promoting the increase of recycling rates result in that recycling companies tend to focus on major metals, such as iron or aluminium, which can globally account for the largest part of the total recycled metals and are more easily recycled.

In summary, applying the exergoecology methodology can be useful for policy makers to obtain more realistic data for the evaluation and loss of mineral capital since it allows for more robust and reliable analysis.

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5.6. RESULTS PENDING FROM PUBLISHING

The aim of the present section is to compare two different types of economies, one dependent in imports and another dependent on exports of raw materials. To accomplish this task two countries have been chosen: Colombia and Spain. As two very different countries are going to be compared, additional information and help was needed. Therefore, this study was conducted with Luis Gabriel Carmona, from the Faculty of Environmental Sciences of the Universidad Piloto de Colombia (Bogotá, Colombia), and with Kai Whiting, from the Faculty of Engineering of Universidad EAN (Bogotá, Colombia).

Colombia is used as an example of exporting country due to the national and global developments occurring in its extractive industry. Firstly, mining and hydrocarbons form an important part of the drive for development, evidenced by the government's vision to become a mining nation by 2019, and as established by the Mining and Energy Planning Unit of the Ministry of Mines and Energy (Unidad de Planeación Minero Energética, 2006).

Spain was selected following a general analysis of European Union mineral trade, carried out in the previous chapter, as an average and representative importing and consuming Member State. This comparative study will be carried out using the year 2011 as a model.

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Article

Physical Assessment of the Mineral Capital of a Nation: the Case of An Importing and An Exporting Country.

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Abstract: Intensified mineral consumption and reserve depletion means that it is becoming increasingly important for policymakers to account for and manage national mineral capital. Exergy replacement costs (ERC), an indicator based on the second law of thermodynamics, provides a physical value of mineral loss. When only a unit mass analysis is used, the role of scarcer minerals, such as gold, is obscured. ERC can identify those minerals which are most critical and more difficult to re-concentrate. This paper compares the mineral depletion of that of Colombia and Spain for 2011, both in mass and ERC terms. The Colombian mineral balance for that year is predominately based on fossil fuel extraction and exports, whilst Spain produced industrial minerals but relied heavily upon metals and fossil fuel imports. Using exergy replacement costs, an economic analysis was carried out to determine the impact of mineral extraction, in monetary terms, should the cost of re-concentrating such minerals be taken into account. In 2011, the GDP derived from the extractive sectors of either country did not compensate the mineral resource loss, meaning that mineral patrimony is not being properly evaluated.

Keywords: exergy analysis; exergy replacement costs; domestic material consumption; assessment of mineral trade; foreign dependency

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1. Introduction

Mineral resource depletion and mineral capital management are critical issues that need to be addressed objectively and efficiently on an international scale across disciplines and professions. According to Krausmann et al. [1] the global total of material extraction has multiplied eightfold since the beginning of the 20th century. The highest increase corresponds to construction minerals and ore/industrial minerals, which grew by a factor of 34 and 27 respectively. In the European Union, domestic material consumption (DMC) is the main flow indicator within material flow accounting (MFA), a system which quantifies extractive activities in tonnes [2]. DMC measures the annual amount of raw materials extracted nationally, plus imports minus exports. A related concept is domestic extraction which considers the annual amount of raw materials (except water and air), extracted on a national level. The ratio between domestic extraction (DE) and DMC may be used to indicate national dependence on mineral extraction and trade, hence why Weisz et al. [3] refer to it as a “domestic resource dependency” ratio. One way to complement this ratio is through exergy replacement costs (ERC) [4].

ERC quantitatively evaluate the effort, or useful energy, needed to re-concentrate extracted mineral wealth with current best available technology. ERC depend on the mineral’s composition, a deposit’s average ore grade and the energy intensity of the mining and beneficiation process. Consequently, scarcer minerals, such as gold or mercury, carry more weight in this non-conventional accounting process, than the common minerals of, say, limestone or phosphate rock. This is useful because mass, the predominate measure of resource extraction, and used in the DMC, does not take quality into consideration and is thus not robust enough to properly assess the loss of mineral capital. The quality of a mineral deposit is a key consideration when it comes to evaluating sustainable development, specifically in terms of mineral scarcity and criticality. Quality and not just quantity measurements, translate into a more reliable set of results from which national and international policymakers can improve sustainable assessments and make informed decisions. These themes are currently under discussion and of foremost importance in various States [5, 6, 7].

2. Methodology

Using a thermoeconomic approach, via the unit exergy and more specifically ERC, the authors undertake a comparative case study between an exporting (Colombia) and importing (Spain) country to assess the effect trade has on their respective mineral capital. Exergy, and specifically, its application in the novel thermoeconomic branch of Physical Geonomics, first introduced by Valero [8], is one method that can, through its objective measure of quality, permit a more rigorous data analysis of mineral depletion. Exergy has been traditionally used to quantitatively measure any energy, such as heat, in terms of its pure forms (mechanical work or electricity) and may be used as an efficiency gauge which states the maximum amount of work that can be obtained when a system is brought to equilibrium with the surrounding environment. This is because from a physical perspective, and according to the Second Law of Thermodynamics, energy is always conserved at the expense of exergy, which is always destroyed, unless the process is 100 percent reversible. In the same way, exergy can be used to assess the quality of material flows such as mineral resources [9, 10].

The mineral capital assessment is accomplished through ERC, on the basis that the greater the difference between the concentration of a randomly dispersed mineral in the Earth’s crust (x_c) to that in an accumulation that could be mined

(x_m), the greater the exergy registered. This in turn explains why the exergy (and energy) consumed in mining increases exponentially, tending towards infinity, as concentration and particle size decreases. The key to making an exergy analysis suitable for any abiotic resource evaluation – that of minerals as well as water – is the appropriateness of the chosen reference point. Reference baselines that could be used include the conventional Reference Environment [11] or the commercially dead planet, Thanatia [12]. The former is commonly used to assess the chemical exergy of elements. However, it is rejected in this instance because it does not consider the exergy required to recuperate minerals in terms of their crustal concentration. The baseline reference employed in this paper is that of Thanatia because it can be used to give an estimate of the Earth's current level of degradation, since it includes a list of minerals with their respective concentrations in the crust [13, 14]. The latter constitutes the lower ore grade limit. Taking this into account, the concentration exergy of each mineral can be calculated as follows (Equation 1):

$$b_{c,i} = -RT^0 \left[\ln x_i + \frac{(1-x_i)}{x_i} \ln(1-x_i)\right] \quad (1)$$

Where x_i is the concentration of substance i, R is the gas constant (8.314 J/molK) and T^0 is the reference temperature (298.15 K). Note, this formula is only valid for ideal gas mixtures and when no chemical cohesion among the substances exists. It is valid for solid mixtures.

The difference obtained between the concentration exergies of a mineral concentration in a mineral deposit (x_m) and that of average concentration in the Earth's crust, i.e. Thanatia (x_c) is the minimum amount of energy that Nature had to spend to concentrate the minerals in a deposit (Equation 2).

$$\Delta b_c = b_c(x = x_c) - b_c(x = x_m) \quad (2)$$

The exergy replacement costs (b^*) are calculated as follows (Equation 3):

$$b^* = k(x_c) \cdot \Delta b(x_c \rightarrow x_m) \quad (3)$$

Where k is a dimensionless variable that represents the unit exergy cost of a mineral, defined as the ratio between the energy invested in the real obtaining process for mining and concentrating the mineral, and the minimum theoretical energy required if the process from the ore to the final product was reversible.

Therefore, k is a measure of the irreversibility of man-made processes and amplifies maximum exergy by a factor of ten to several thousand times, depending on the commodity analyzed.

Another way to understand the relevance of mineral capital losses, caused by domestic extraction, is to convert exergy replacement costs into money, through current energy prices. Together with the DMC ratio, of equation 4, the impact that economic costs associated with mineral depletion may have on GDP and sustainable development can be assessed.

$$DMC\ ratio = \frac{domestic\ extaction\ (DE)}{\text{extraction} + \text{imports} - \text{exports}} \tag{4}$$

Note that equation 4 can be calculated in terms of mass or exergy units, and DE can be replaced with import or export flows to evaluate their respective ratios.

The monetary cost of reversing the extractive process using current energy quantities and prices, can be represented in equation 5:

$$Monetary\ costs\ of\ ERC\ = b^* \cdot p \tag{5}$$

Where, p corresponds to the national or world market price of the total amount of energy, from a given source (coal, oil, gas, electricity), required to reverse the mining and beneficiation process and effectively place a mineral back into its original deposit, using current best available technology.

In the case of fossil fuels, economic costs can be directly calculated using their corresponding market prices of the year under consideration. The prices used are the price per barrel in the case of oil, the UK Heren NBP Index price for natural gas and the Northwest Europe marker price for coal [15, 16]. For non-fuel minerals the authors considered a range. The lower boundary is calculated assuming that coal is used to re-concentrate mineral capital. The upper boundary calculates with electricity. Electricity prices were obtained from the national statistics services of both respective countries.

The minerals considered are presented in table 1. The detailed methodology for obtaining the non-fuel mineral data, included in this table, is described in [17]. In the case of fossil fuels, since once they are consumed and burned they cannot be replaced, their exergy content corresponds to their high heating values [18].

Table 1. Exergy replacement costs of the minerals considered in this study [17]).

Substance	Mineral ore	Exergy Replacement costs (GJ/ton)	Minerals analysed for Colombia	Minerals analysed for Spain
Non fuels				
Aluminium	Gibbsite	627.3		X
Antimony	Stibnite	474.5		X
Arsenic	Arsenopyrite	399.8		X
Bismuth	Bismuthinite	489.2		X
Cadmium	Greenockite	5898.4		X
Chromium	Chromite	4.5		X
Cobalt	Linaeite	10871.9		X
Copper	Chalcopyrite	110.4	X	X
Fluorspar	Fluorite	182.7		X
Gold	Native gold	583668.4	X	X
Gypsum	Gypsum	15.4		X
Iron ore	Hematite	17.8	X	X
Lead	Galena	36.6		X
Limestone	Calcite	2.6	X	X
Lithium	*Li* in brines	545.8		X
Manganese	Pyrolusite	15.6		X
Mercury	Cinnabar	28298.0		X
Molybdenum	Molybdenite	907.9		X
Nickel	Pentlandite	761.0	X	X
Phosphate rock	Fluorapatite	0.4		X
Potassium	Sylvite	1224.2		X
Silicon	Quartz	0.7		X

Silver	Argentite	7371.4	X	X
Sodium	Halite	44.1		X
Tin	Cassiterite	426.4		X
Titanium	Ilmenite	4.5		X
Uranium	Uraninite	901.4		X
Wolfram	Scheelite	7429.3		X
Zinc	Sphalerite	24.8		X
Zirconium	Zircon	654.4		X
Fossil fuels				
Coal		24.3 – 31.6	X	X
Natural Gas		39.4	X	X
Oil		44.0 – 46.3	X	X

Data categories include the following: mineral capital loss includes extraction, imports, exports and recycling for 2011, as a common reference year [19, 20].

Colombian data is taken predominately from the Colombian Mining Information System (SIMCO) and Ministry of Mines and Energy (Ministerio de Minas y Energía). Copper recycling was taken from the National Register for the Generation of Hazardous Waste (Registro Nacional de Generadores de Residuos Peligrosos). For Spain, the data comes from the Ministry of Industry, Energy and Tourism of Spain (Ministerio de Industria, Energía y Turismo) and Spanish Statistical Office (Instituto Nacional de Estadística) The import/export information was taken from the Chamber of Commerce (Cámara de Comercio). Spanish mineral recycling rates were obtained from a report published by the United Nations Environment Programme [21]. United States Geological Survey (U.S.G.S.) statistics were used as supplementary information for both Colombia and Spain [22, 23].

The input and output flows were represented in a Sankey diagram to support visual understanding. Note, even though recycling can be considered both an input and an output, such flows, in this case, were considered only as an output, given that the analysis is carried out for a single year and subsequently it is not logical to assume that the amount recycled in that year was produced that same year.

3. Colombian and Spanish mineral resources

3.1. Colombia

In 2011, 40% of Colombian land had either been licensed or solicited for mining concessions [24]. Colombia represented the fifth largest economy in Latin America in 2011 [25]. In addition, 11.3% of the GDP corresponded to the mining sector; mineral export specifically, in monetary value, accounted for 55% of the country's total exported goods in 2011 [26].

According to British Petroleum [16], Colombian proven reserves of oil and natural gas both represent 0.1% respectively of the global reserves. Proven coal reserves, meanwhile, correspond to 0.8%. In 2011, Colombia was the number one coal producer in Latin America, the tenth producer of coal globally and the fourth largest thermal coal exporter [22].

Regarding non-fuel minerals, the country is the number one producer of emeralds in the world, the number one producer of nickel and coal in South America, the only producer of platinum of Latin America and the tenth largest producer of gold in the world. In 2011, non-fuel mineral production was led by limestone (97%) and iron (1.2%) followed by nickel, copper, gold, silver and platinum (accounting for 0.9% in total) [27].

3.2. Spain

In 2011 Spain was the third global producer of gypsum and the sixth producer of fluorspar and Spain's mining and mineral processing industries contributed to 0.8% of Spain's GDP [23].

According to British Petroleum [16], the country does not have proven reserves of oil nor natural gas but does have 530 million tonnes of coal reserves, equivalent to less than 0.1% of world coal reserves. Spain has an almost negligible extraction of natural gas and oil, leaving coal as the most important fuel. In 2011, approximately 6.7 million tonnes of anthracite, bituminous and subbituminous coal were extracted.

The highest level of extraction of any mineral is that of limestone, with 129.6 million tonnes extracted in 2011, a significant amount when compared to the 7.8 million tonnes of gypsum extracted that same year [28]. Regarding metals, there are still some mines, in the northern and eastern zones of the country that extract copper, gold, lead, silver and zinc.

4. Comparative case studies: Colombia and Spain

Colombia is investigated due to the national and global developments occurring in its extractive industry and its desire to export. Mining and hydrocarbons form an important part of the drive for development, evidenced by the government's vision to become a mining nation by 2019 [29]. Spain was selected following a general analysis of European Union mineral trade, where it was shown be an average and representative importing and consuming Member State [30].

4.1. Analysis in unit tonnes

a) Colombia

As seen in figure 1A, Colombian production and export predominate over imports, recycling and consumption. Fossil fuel extraction represents 91.2% of the total. Limestone is the second most extracted mineral, accounting for 8.6%, and contributing, albeit in small quantities, to the export market. The remainder (0.2%) corresponds to iron, nickel, copper, gold, silver and PGM (platinum group metals). Fossil fuel imports represent less than 0.01% of the total mineral balance whilst the contribution of recycling is almost negligible.

Figure 1B is obtained upon removing both fossil fuels and limestone data from figure 1A. It is subsequently much easier to see that there is an appreciable consumption of iron and that nickel is the most important exported metallic mineral. Even when fossil fuels and limestone are removed from the Sankey diagram, copper, gold, PGM and silver production is still not large enough to register.

b) Spain

Figure 1C is the graphical representation of the Spanish mineral balance. Limestone predominates over the rest of the materials, representing 86%, in mass terms, of the total fuel and non-fuel mineral production. Imports represent 19.3% of the global mineral balance, and correspond to that of oil, natural gas and aluminium. Recycling and exports do not play a significant role, accounting for only 2.6% between them. If, as before with Colombia, data related to fossil fuels and limestone is removed from figure 1C, to create figure 1D, gypsum, salt, potash and feldspar were the most extracted substances in 2011. Gypsum remains one of the most extracted and exported substances in the country, although a little more than half of the production is consumed domestically. Metals, such as aluminium, iron, copper and zinc, are imported.

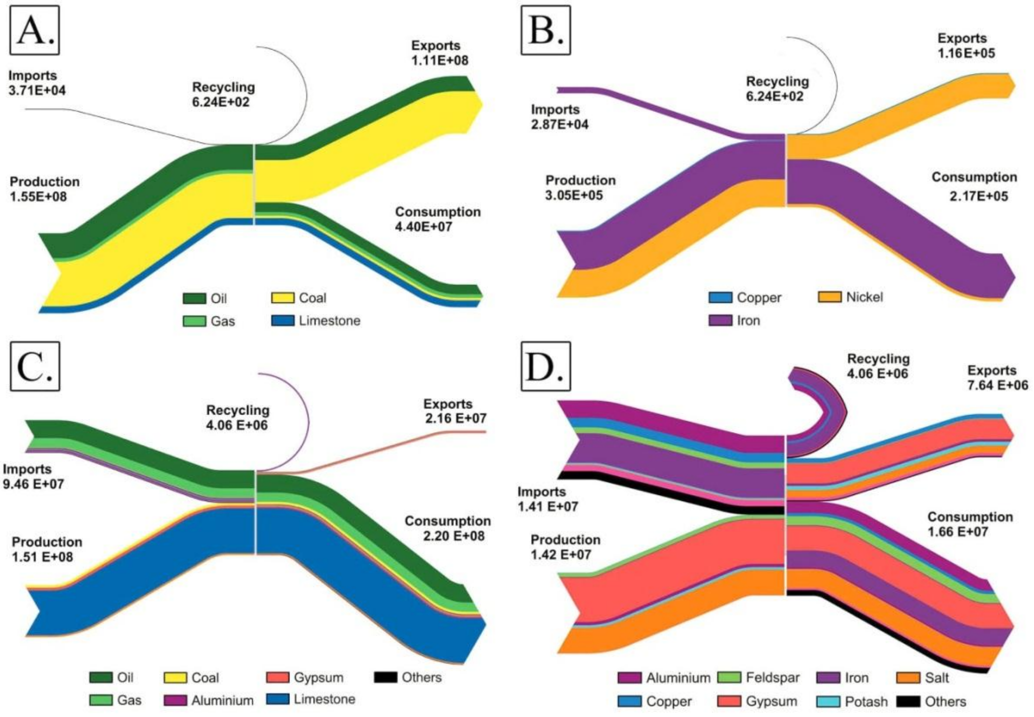

Figure 1. Sankey diagrams representing mineral balance for the year 2011 expressed in tonnes. (**a**) Colombian mineral balance; (**b**) Colombian mineral balance without fossil fuels and limestone; (**c**) Spanish mineral balance; (**d**) Spanish mineral balance without fossil fuels and limestone.

4.2. Comparative analysis in exergy replacement costs

a) *Colombia*

If the 2011 mineral balance is represented, not in mass, but instead in ERC terms (figure 2A), oil and coal remain the most important Colombian commodities. Oil extraction, measured in percentage mass represents 31.1% of the total. This percentage increases to 43.3%, if oil extraction is measured using exergy replacement costs. The same thing happens for gas extraction (going from 4.6% to 7.2%), and coal extraction changes too (going from 55.4% to 47.6%). Exports, for their part, correspond to 73% of all mineral resources mined nationally.

If fossil fuel data is discarded from the Sankey diagram (to create figure 2B), the iron or nickel that played an important role in unit mass, become less relevant when considered in exergy replacement terms. Gold, almost exclusively extracted for the export market, occupies a much more significant position. Its mass is almost negligible but its exergy replacement cost constitutes 35.3% of the total, as it requires more energy intensive processes, and thus is more difficult, to concentrate (or re-concentrate) than say limestone, iron or copper. Comparing the average energy intensity of copper and gold, in the former it is 22.2 GJ per tonne and in the case of gold it is 143 GJ per kilo [31, 32]. The importance of limestone extraction thus decreases. It contributed to 97.7% of the non-fuel mineral mass balance but only 37.8% of the exergy replacement costs. This is caused by the predominance of fossil fuel extraction and export, which masks the relevance of other minerals. If fossil fuel data are removed from the Colombian mineral balance, 0.21% of the total comes from imports, when expressed in tonnes, and 17.58 % when presented as exergy replacement costs. Iron is the most imported metal.

b) *Spain*.

The significance of both oil and gas imports is identical, whether expressed as exergy replacement costs (figure 2C) or mass (figure 1C). The most striking variation corresponds to limestone. Limestone extraction measured 86% of the total domestic extraction in mass units but decreases to 23% when using exergy replacement costs. Exports correspond to 23% of the total output minerals. Potash, gypsum and salt (halite) are the most exported commodities.

Aluminium, which has the highest level of import and consumption of any metal in Spain, experiences a notable difference. In terms of percentage in tonnes, it contributed little. Represented through exergy replacement costs, however, and aluminium accounts for 32% of the total import. If as before, fossil fuels and limestone data are removed from the scenario (figure 2D), the role of potash and halite in national production and export becomes more apparent.

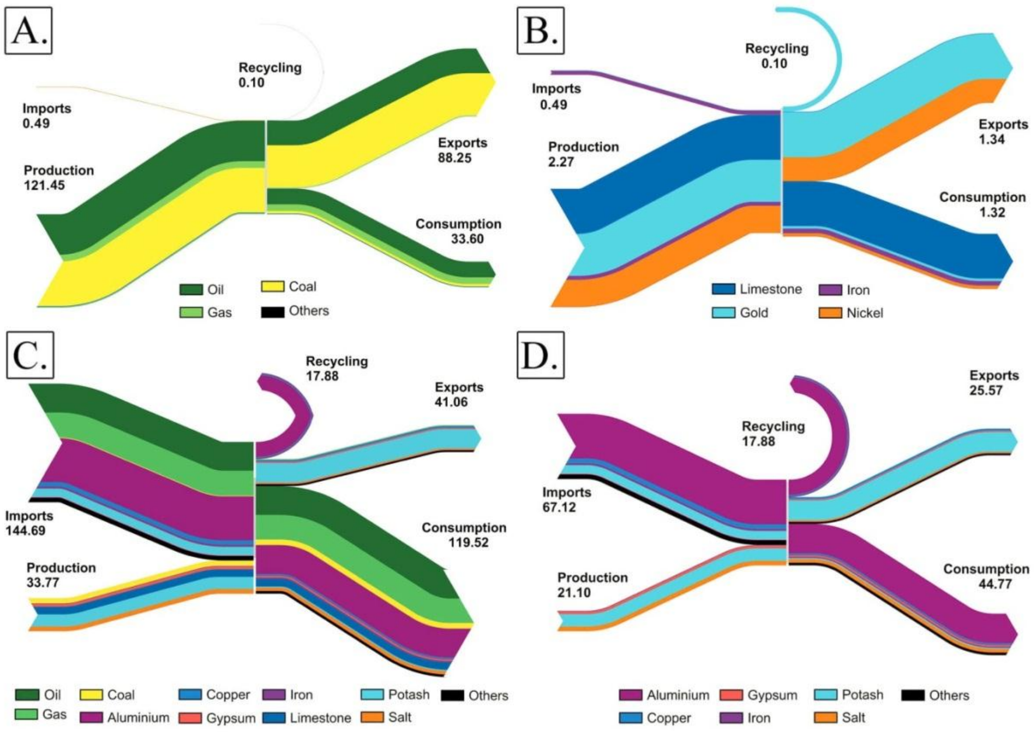

Figure 2. Sankey diagrams representing mineral balance for 2011 expressed in exergy replacement costs. (**a**) Colombian mineral balance; (**b**) Colombian mineral balance without fossil fuels; (**c**) Spanish mineral balance; (d) Spanish mineral balance without fossil fuels and limestone.

A summary of the percentage total in mass terms and in exergy replacement costs of production, imports, exports, recycling and consumption for both countries can be found in the Table 2.

Table 2. Percentages for production, imports, exports, recycling and consumption. 2011 data expressed in mass terms and in exergy replacement costs for Colombia and Spain.

		Colombia (mass)	**Colombia (ERC)**	**Spain (mass)**	**Spain (ERC)**
Inputs	Production	99.98	99.60	61.42	18.92
	Imports	0.02	0.40	35.58	81.08
Outputs	Exports	71.57	72.37	8.80	23.01
	Recycling	<0.01	0.08	1.65	10.02

Consumption (P+I-E-R)	28.42	27.55	89.54	66.97

In both countries, mineral recycling is extremely low, accounting for less than 0.01% and 1.65% in Colombia and Spain respectively in mass terms. Comparing the mineral balance in mass terms, one can see that the Colombian economy is one of export (71.57%). In 2011, 3.9% of its total exports went to Spain. In the period January to December, Spanish imports of Colombian minerals increased by 204.4%, mainly due to fuels and their derived products [33]. In fact, Spain depends almost entirely on imported fossil fuel supply and almost everything that is imported or Spanish produced is consumed within the country's borders.

On comparing the values in mass and exergy replacement costs terms, it becomes clear that Colombian net values remain within the same magnitude. For Spain, the difference between mass and exergy replacement percentages are noticeable, since Spanish mineral imports consist essentially of those minerals that require highly energy intensive processes to re-concentrate them from a dispersed state (*i.e.* Thanatia) back into the original natural deposit (*i.e.* the condition of mineral's existence before having been mined).

4.3. Domestic Mineral Resource Dependency Ratio

For Colombia, the domestic mineral resource dependency ratio (DE/DMC), in the case of non-fuel minerals, is greater than one, indicating that the country is self-sufficient for the minerals analysed; as evidenced by figure 1A and figure 2A. In the case of I/DMC, Colombia depends on an external supply of iron, which is subtly identified by the value of exergy replacement costs. For E/DMC, as stated before, gold and nickel were the main minerals exported, and this higher quality, as opposed to quantity, is the main characteristic reflected in these results.

In the case of Colombian fossil fuels, the DE/DMC ratio, when mass is used, is high. This is because, and as aforementioned, Colombia is an exporting country - around 78% of the fossil fuels extracted in 2011 were sent abroad. The DE/DMC ratio decreases by approximately 20% when expressed in exergy replacement costs. As shown in figure 1A, coal has a significant role in Colombian exports and since all types of coal have lower high heating values than either oil or natural gas, the total exergy value is lower than when expressed in mass terms.

Since the order of magnitude is noticeable, and in an effort to maintain representativeness in the results, the data for non-fuel minerals and fuel minerals has been kept separate, as shown in Table 3.

Table 3. Ratios between domestic extraction and domestic material consumption (DE/DMC), imports to DMC (I/DMC) and exports to DMC (E/DMC) for Colombia and Spain for the year 2011. Data are expressed in mass terms and in exergy replacement costs.

		DE/DMC		**I/DMC**		**E/DMC**	
		Mass	**Exergy**	**Mass**	**Exergy**	**Mass**	**Exergy**
Colombia	Non-fuel minerals	1.40	2.14	0.00	0.02	0.01	1.26
	Fossil fuels	4.63	3.69	0.00	0.00	3.63	2.69
Spain	Non-fuel minerals	0.97	0.45	0.10	1.32	0.05	0.54
	Fossil fuels	0.08	0.07	0.93	1.13	0.16	0.20

As for Spain, and in the case of non-fuel minerals, when domestic mineral resource dependency is considered in mass terms, it appears not to depend highly on import (0.97; with one or higher indicative of a low domestic mineral resource dependency). Yet, this value reflects the fact that imported non-fuel minerals are masked, in mass terms, by the sizable quantity of construction minerals (in terms of tonnes) that Spanish industry provides for its own market demand. Spanish limestone and gypsum, for example, account for 96.5% of the total.

When domestic mineral resource dependency is calculated using ERC, DE/DMC ratio drops by slightly less than half (0.45). This, along with the elevated value of the I/DMC ratio in exergy terms, indicates that Spain relies on scarcer mineral imports, such as those of aluminium, copper or iron. These minerals have higher exergy replacement costs.

For the export dependency ratio (E/DMC), the most significant 2011 mineral export, in terms of tonnes, was potash. Given its elevated exergy replacement cost, its role becomes more noticeable when considered in exergy rather than mass units.

Since Spanish domestic extraction of fossil fuels is almost negligible, the DE/DMC ratio confirms that Spain depends strongly on external sources, which is also demonstrated by the high I/DMC ratio.

On further analysis, Colombian coal export dependency could present a problem should the market turn to cleaner fuels. Precious metal demand places great pressure on existing reserves and could create future development issues. For Spain, the ERC show a high import dependency on scarcer minerals. The country should either increment domestic production for these minerals or reduce/adapt the activities that require an intensive use of rarer elements.

4.4. Economic analysis for Colombian and Spanish mineral balance

According to table 4 and figure 3, if Colombia was charged with having to re-concentrate those minerals that it had extracted in 2011, the GDP of $38 billion (USD, 2011 price) generated by its extractive industries would not cover the ERC monetary equivalent of approximately $56-59 billion (USD), regardless of the energy source used.

For Spain, the contribution of the extractive industry was approximately $11.2 billion (USD). This is substantially less than the theoretical amount required to re-concentrate the extracted assets, upon considering the upper boundary. This issue appeared in 2009, as studied by Valero et al. [34] who discovered that on average prices were 39 times lower than what they needed to be in order to reflect the loss of mineral capital, calculated via exergy replacement costs.

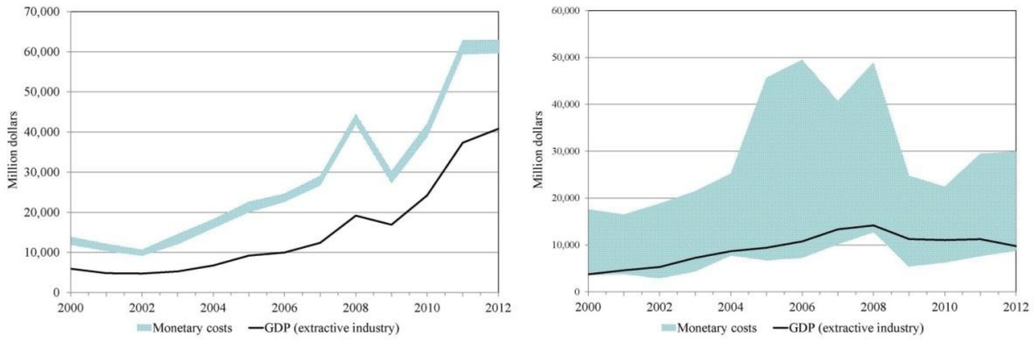

Figure 3. Monetary equivalent of ERC and GDP generated by the extractive sector for Colombia (left) and Spain (right) from 2000 to 2012.

Table 4. Monetary costs associated to the mineral extraction in Colombia and Spain for 2011.

		Colombia	**Spain**
Exergy (total, Mtoe)		121.45	33.77
Monetary costs (billion $)	*Lower boundary*	55.94	7.63
	Upper	59.40	29.48

	boundary		
% GDP	*Lower boundary*	16.67%	0.52%
	Upper boundary	17.69%	2.02%

5. Conclusions

A DMC analysis, with exergy replacement costs, makes it possible to evaluate not only the quantity but the quality of international flows transferred between nations. This allows for a more complete picture of mineral dependency and sustainable development.

The economic analysis indicates that Colombia would have lost a monetary equivalent of $56 to $59 billion (USD), if it had to re-concentrate its mineral deposits using energy derived from either coal or electricity, a figure higher than the Colombian mining sector's contribution of $38 billion USD. Spain's alleged losses would be considerably lower than Colombia's but still between $7 and $29 billion (USD). That said, given the Spanish reliance on import most of the country's ERC would be allocated to Colombia and the other trade partners, which supply the mineral demand beyond Spain's own domestic production capabilities.

If exergy replacement costs are considered, the theoretical figures presented in this paper can link market prices to values that more readily correlate to physical costs. Currently, the fact that the true cost of mineral resource extraction is not considered in ERC terms means that current rates of extraction at 2011 prices are not sustainable.

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Author Contributions

These authors contributed equally to this work.

Conflicts of Interest

The authors declare no conflict of interest.

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5.7. COMPLEMENTARY RESULTS

In this section, complementary results for the already published papers, both for the analysis of the mineral trade and exergy assessment of Spanish mineral resources and the European Union, can be found.

5.7.1. AN EXERGOECOLOGICAL ANALYSIS OF THE MINERAL ECONOMY IN SPAIN

a) Spanish mineral resources and exergy assessment

Historically, Spain has always been a territory rich in mineral resources and the mining sector in Spain has been proved quite important for the economy. Even if the Romans where already extracting gold in “Las Médulas” (León) during the first century b.C., contemporary mining started in Spain around 1820, where there was a progressive liberalization of mining and when the first mining boom took place in “Sierra de Gádor” (Almería) (Pérez de Perceval & López-Morell, 2013). The mining activity of the XIX century was dominated by small companies, mostly constituted by national capital. It was not until the last decades that the big companies started their activity. During that period, mostly metal extracting mines were opened, such as the ones of the Río Tinto zone (Huelva).

At the beginning of the 20th century, mainly metallic minerals were extracted in the Spanish territory, such as copper, iron and lead. However, there has been a change in the tendency of the mining sector in the second half of the century, and the extraction of industrial minerals (construction materials) related to the emergence of housing bubbles made up the bulk of the total production (Carpintero, 2005).

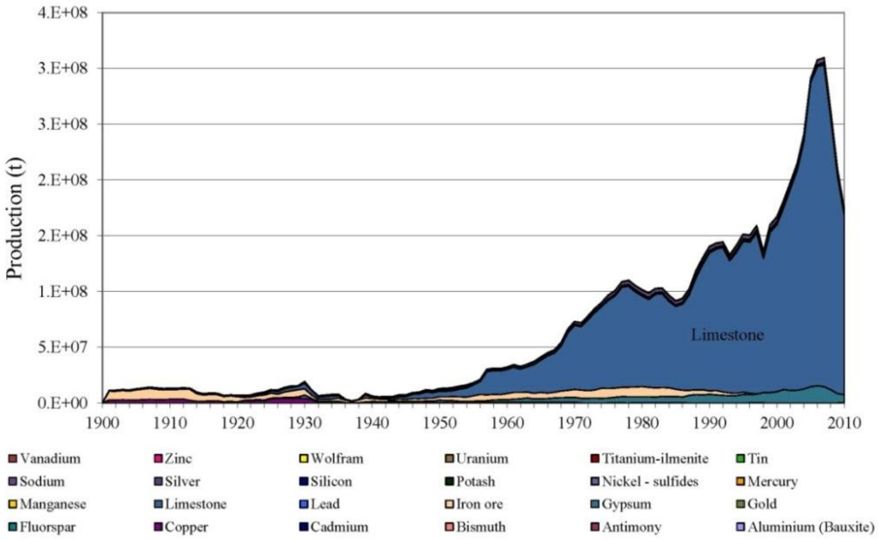

Figure 30. Spanish mineral cumulative extraction from 1900 to 2010 for selected non-fuel minerals.

For the 1900-2010 period limestone accounted for almost 82% of the total mineral production (Figure 29), being the domestic extraction in 2009 around 195 million tonnes, very high numbers when compared to the 8 million tonnes of gypsum, the second most extracted commodity that year, or the 4 million tonnes of salt extracted. For this reason it seems necessary to temporarily remove limestone extraction data from the diagram so the overall mineral balance can be better appreciated (Figure 30).

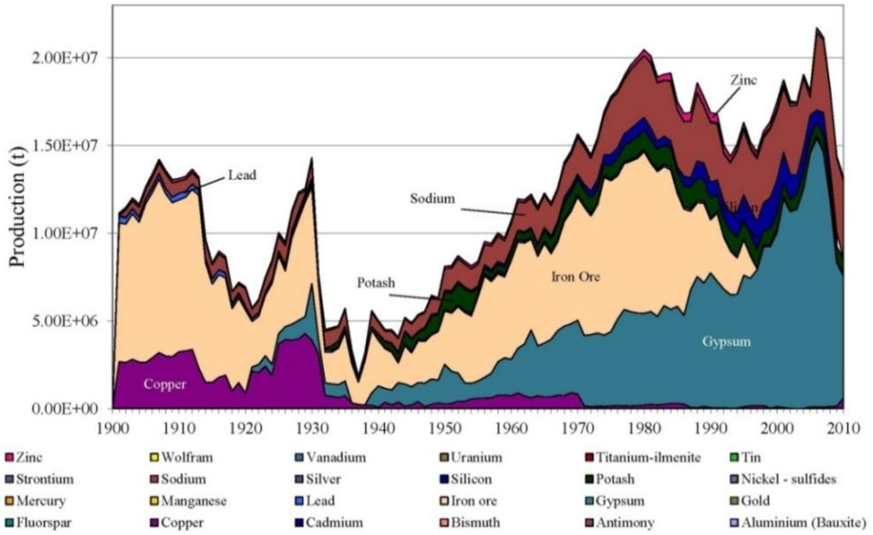

Figure 31. Spanish mineral cumulative domestic extraction from 1900 to 2010 for selected non-fuel minerals.

Removing limestone from the diagram the domestic production of other minerals, such as copper, iron ore, sodium, potash, lead or zinc, stands out, still there are many other minerals whose production is so low that it still doesn’t show on the diagram.

Several minerals that were not taken into account in this study due to the limited data but that are nonetheless important for the domestic mineral market are natural sodium sulfate, being Spain the leading and only producer in Europe, slate, special clays, sepiolite, having 70% of the world resources and celestite, being with 165,000 tonnes the first worldwide producer in 2014 (USGS, 2015).

Regarding fossil fuels, the country has limited energy resources. Spain produces considerable amounts of coal (bituminous, subbituminous, lignite and anthracite) and smaller amounts of oil, natural gas production can be deemed almost negligible (Figure 31).

Coal reserves and deposits are mainly concentrated in the NW and in the central-eastern zone, although there are small deposits scattered along the country. Generally the deposits are low quality and they are lignite-sub-bituminous rank (Suárez-Ruiz & Jimenez, 2004). Being coal the most indigenous energy source, there has not been lignite production since 2008 and the general coal production has drastically decreased since the 1980s. The proved reserves are estimated to be 530 Mt between anthracite and bituminous coal (200 Mt) and subbituminous coal and lignite (330 Mt), the Spanish reserves corresponding to around 0.1% of the world total coal reserves (British Petroleum, 2014).

Oil is extracted in the eastern and northwestern part of the territory, and also some offshore deposits have been discovered recently in the Canary Islands and in the Bay of Valencia. At the end of 2012 the reserves of petroleum were estimated to be 150 million barrels while proved reserves of natural gas were 2.5 billion cubic meters (Instituto Nacional de Estadistica, 2013; U.S. Energy Information Administration, 2013).

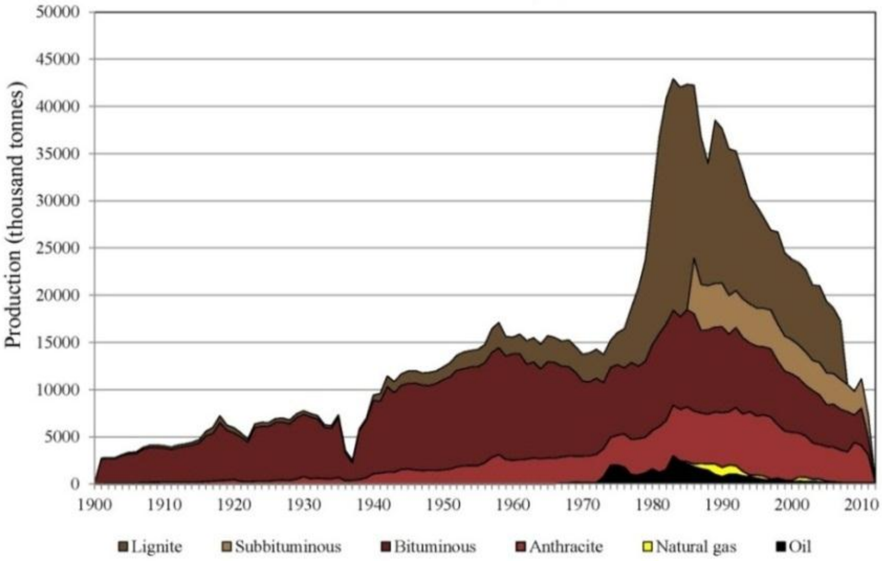

Figure 32. Spanish fossil fuel production from 1900 to 2010 (Estadistica Minera de España).

Throughout the years, many mines have closed due to the decreasing ore grade of metallic minerals, mineral depletion and low profitability. With globalization, it has become cheaper and easier to simply import the minerals that were needed or directly the by-products. As it can be seen in Table 19, there has been a severe decrease in the number of mines extracting fossil fuels and metallic minerals between 1995 and 2010, 66% and 60% respectively. One of the minerals most affected by this decrease was iron. At the beginning of the 1960s there were more than 300 iron mines in operation but at the end of the same decade there were only 90 mines remaining (Carpintero, 2015). A similar situation is the one of copper, with 22 operating mines in 1961 but with only two still in operation. Regarding construction minerals and non-metallic minerals, there is an important increase, 11% from 2000 to 2007, closely related to the housing bubble (Carpintero, 2005).

Table 19. Evolution of the number of mines or mining groups by types of substances. (1) Includes ornamental rocks. (Estadística Minera de España).

	1975	**1985**	**1995**	**2000**	**2007**	**2010**	**2012**
Fuel minerals	162	268	135	84	62	46	46
Metallic minerals	148	71	15	10	2	6	7
Non-metallic minerals	460	301	190	185	114	192	2,566
Construction minerals	3,666	2,981	3,158	3,485	4,303(1)	3,368(1)	589
Total	4,436	3,621	3,498	3,764	4,181	3,612	3,208

Accordingly, there has also been a decrease in the value of the mineral production in Spain (Table 20). Whilst the economic crisis seriously affected the construction and industrial mineral sector, it approximately accounted for 60% of the total mineral value, reaching up to 70% in 2008. The progressive closure of coal mines reduced the production of energetic products but this decrease was approximately compensated with a slight increase in oil production. Regarding metallic minerals, copper mining accounted for 11.6% of the total amount in 2009, being one of the most important commodities.

Table 20. Evolution of the value of mineral production in thousand euros (Instituto Geológico y Minero de España, 2010, 2011, 2015).

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2012**
Fuel minerals	663,704	657,203	657,205	574,603	543,623	522,362	453,174
Metallic minerals	128,982	178,052	147,676	45,485	179,416	396,538	716,872
Construction and industrial minerals	2,547,246	2,814,465	2,979,066	2,859,028	2,339,663	2,064,376	1,661,312
Ornamental rocks	632,530	709,644	681,451	635,691	458,464	443,868	412,046
Total	3,972,462	4,359,365	4,465,398	4,114,807	3,549,581	3,427,144	3,244,404

Nowadays, only a limited number of mines are still in operation, being dedicated most of them to the extraction of construction and industrial minerals. In 2011 only seven metallic minerals mines were still operating, extracting small amounts of zinc, copper, gold, silver, tin, lead and tungsten (Table 21).

Table 21. Metallic mineral mines operating in Spain as of 2011 (Estadística Minera de España, 2011).

Elements	Province
Cu (±Au, Pb,Zn)	Huelva (Andalucía); Sevilla (Andalucía)
Au-Ag	Asturias (Asturias)
Sn	Salamanca (Castilla y León)
Sn-W	Coruña (Galicia)
Pb-Zn	Granada (Andalucía)
W	Salamanca (Castilla y León)

b) Exergy loss associated to Spanish mineral extraction

Regarding non-fuel minerals, Figure 32 depicts the cumulative exergy replacement costs belonging to Spanish domestic extraction from the years 1900 to 2010. Of the substances analyzed, potash, limestone, copper, gypsum, iron, sodium and mercury clearly stand out from the rest. Among them mercury has the highest value of unit exergy replacement (289,298 GJ/ton), attributable to its low concentration in mines and the consequent use of energy to concentrate it. Even if the mercury extraction was apparently not so remarkable when expressed in tonnes (Figure 32), we can appreciate its relative importance when expressed in exergy cost terms.

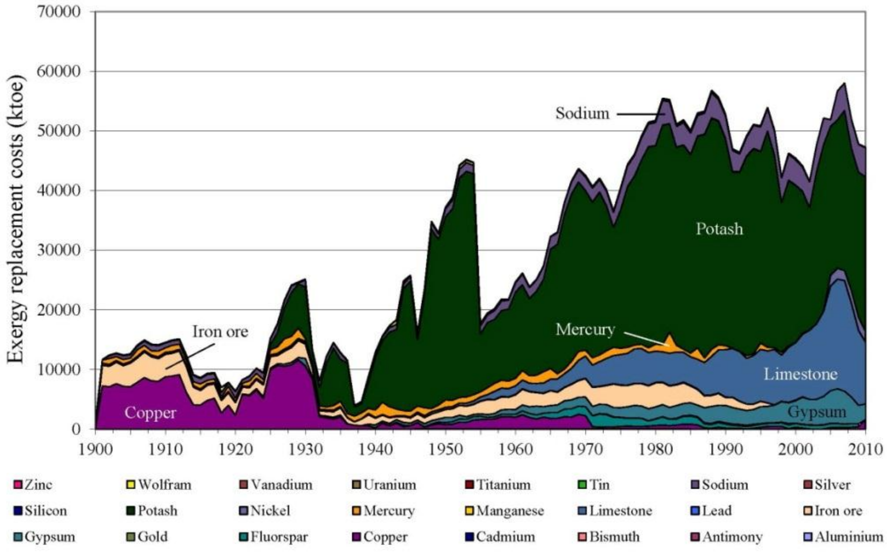

Figure 33. Cumulative Spanish non-fuel mineral exergy consumption from 1900 to 2010.

Leaving aside the overall relevance of limestone extraction, one main difference is the weight of potash, which is much higher when expressed in exergy replacement costs. Additionally, along with metallic minerals such as copper or iron, whose importance in the national domestic extraction market already stood out in mass terms, the weight of other minerals can be appreciated.

In Figure 33 the Spanish cumulative fossil fuel exergy consumption can be observed. As stated before, in the case of fossil fuels their exergy replacement costs can be approximated to their correspondent high heating values. Therefore, the general tendency remains quite similar whether the results are analyzed in tonnes or in exergy cost terms and only subtle differences can be noticed.

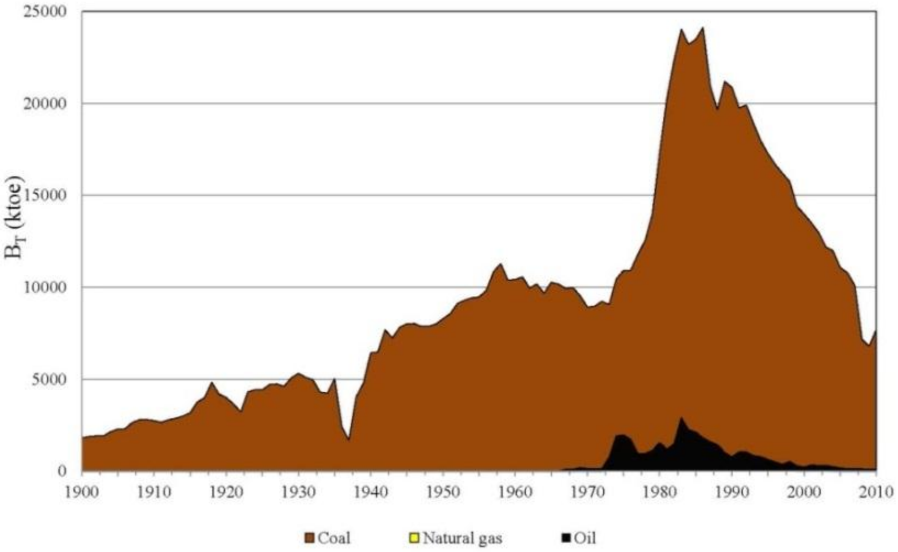

Figure 34. Cumulative fossil fuel exergy consumption from 1900 to 2010 in Spain.

Using the available data of Spanish estimated mineral reserves and knowing the extraction during the last decade the depletion ratios can be estimated. In Spain there is not a comprehensive report available regarding estimated reserves or resources but several reports were made for selected substances during the 1980s and 1990s (Instituto Geológico y Minero de España, 1983, 1984, 1985a, 1985b, 1997; Patterson, Kurtz, Olson, & Neeley, 1986). These data, along with several reports from operating mines (Lundin Mining, 2015; Noble, 2010; Wheeler, 2013) have been used to obtain a lower limit of the Spanish estimated resources. It is important to note that resource and reserves data are just estimations that can change and increase with further exploration and investigation.

A summary of the depletion degree for selected substances can be found in Figure 34.

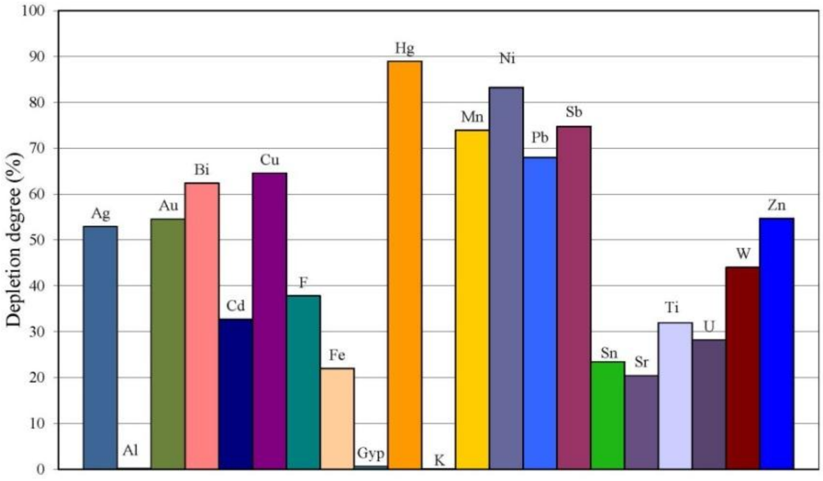

Figure 35. Depletion degree (%) of selected mineral reserves in Spain.

The average depletion ratio is 43.79%, meaning that the Spanish available mineral resources have been almost halved in the last century. According to these data, mercury, nickel and antimony are the most depleted substances while aluminium, potash and gypsum are the least depleted ones. The case of aluminum stands out, but this low number does not seem to be very representative. Aluminium production in Spain is mainly based on bauxite extraction and total domestic extraction is very low when compared to the estimated resources (Patterson et al., 1986), but neither information seems accurate.

A comparative analysis of the depletion rations between Spain and the world is presented in Table 22. Data from world depletion ratios are for the year 2006 (Alicia Valero, 2008). Mercury stands out as the most depleted mineral at world and Spanish level, but due to its toxicity and associated environmental problems there has been an overall decrease in mercury consumption. Demand has fallen significantly in the last 50 years, from 9,000 tonnes a year to 4,000 (UNEP, 2006). The world largest mercury mine, Almadén (Ciudad Real, Spain), stopped primary mercury production in 2004 and since that year there has not been mercury production in Spain. This could explain the high mercury depletion ratio in the case of Spain as and no further exploration studies have been made. At world level, several reports and conferences have shown the negative impacts of mercury use and production and many actions have been implemented in this regard (UNEP, 2012, 2013; World Health Organization, 2014). In 2008, United States of America banned mercury exports from 1 January 2013. The European Union carried out a similar action, banning mercury exports in 2011.

Table 22. Spanish and world depletion ratios for selected substances.

Substance	Spain [%]	World [%]	Substance	Spain [%]	World [%]
Antimony	74.7	72.8	Manganese	73.9	51.9
Bismuth	62.4	41.1	Mercury	89.0	92.2
Cadmium	32.7	66.8	Nickel	83.3	40.0

Substance	Spain [%]	World [%]	Substance	Spain [%]	World [%]
Copper	64.6	50.3	Silver	52.9	78.5
Fluorspar	37.8	48.6	Tin	23.4	75.2
Gold	54.6	75.4	Uranium	28.2	34.8
Iron ore	22.0	27.7	Wolfram	44.0	48.5
Lead	68.0	72.5	Zinc	54.7	68.1

Regarding other substances, only the differences between Spanish and world depletion degree for cadmium, gold, nickel and tin, stand out over the rest. As cadmium reserves data is based on the amount of cadmium estimated in zinc reserves and extraction data comes from refined cadmium in zinc ores, the resulting Spanish depletion degree should not be considered relevant. In the case of gold and tin, the depletion degree in Spain is much lower and the opposite happens with nickel, but again this could be attributed to the lack of reliable information.

As stated before, these data must be taken only as an approximation due to the lack of accuracy of the reserves data and to the limitations of the study but this information can help emphasizing the seriousness of the mineral depletion situation.

In Figure 35 data for domestic extraction for non-fuel minerals is represented in tonnes and in exergy replacement costs for the 1995-2012 period.

In this particular period of time the minerals that experienced a bigger increase in extraction were mainly gypsum and limestone, the latter being very important for building and infrastructure construction. With the boom in the construction sector, extraction increased considerably and when the demand fell again due to the economic crisis the extraction also diminished. In general, non-fuel minerals extraction has seemed to be more dependent on the necessities of bulk material for the domestic market. However for the rest of the minerals, especially in the case the metallic minerals, as explained before, many mines have closed.

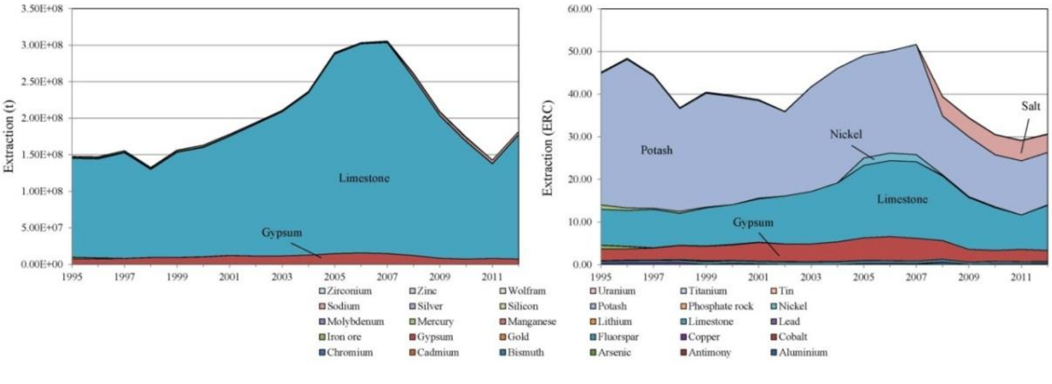

Figure 36. Spanish non-fuel mineral extraction from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

When expressing domestic extraction in exergy replacement costs the main mineral that stands out is limestone, but with lesser extent than before, but still other minerals can be seen now such as gypsum, potash, salt and nickel.

The general tendency of data expressed in tonnes and in exergy replacement costs is more or less equivalent except for the years 2004-2007. In this period, the changes in data expressed in exergy cost terms are less abrupt. Indeed, even if domestic extraction increases, the associated exergy replacement costs remains constant or decrease, although it would be expected to increase as well. This is the result of the change in the domestic extracted minerals; the increase corresponds to lower quality minerals, i.e., that have lower unit exergy replacement costs.

For fossil fuels (Figure 36) we can see that there is a clear decrease tendency in domestic extraction and that coal was the main fossil fuel extracted in Spain during this period of time.

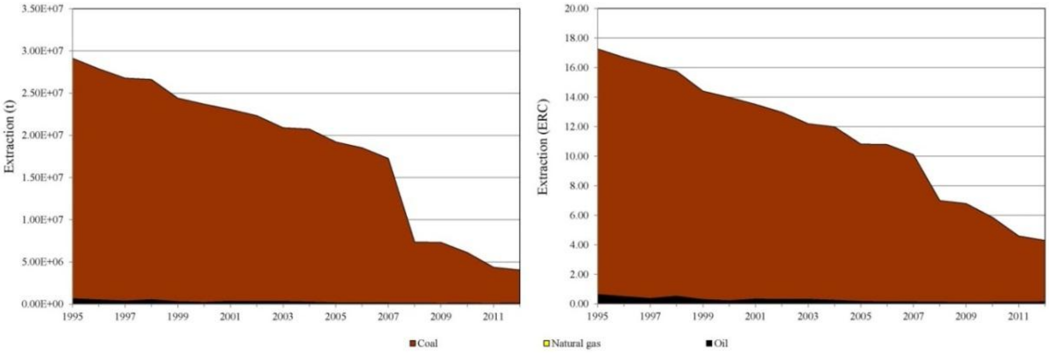

Figure 37. Spanish fossil fuel extraction from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

This tendency of reducing the domestic extraction of fossil fuels does not imply a reduction of the consumption. With the current economic crisis, consumption of fossil fuels has in fact diminished, but the principal explanation for this general decrease is that Spain extracts less. This is caused not only by the environmental policies and the elimination of the subsidies, but also due to the geological conditions and structural complexity of the deposits, making them economically unprofitable for most cases. This results in part in an increase of imports, shifting the environmental burden associated and the loss of resources to other countries.

In the case of fossil fuels, as coal was predominantly extracted, both the data in tonnes and in exergy cost terms follow the same trend and are almost identical. This is because, as explained before, the exergy of fossil fuels is calculated by multiplying the tonnage by a factor close to its HHV. Still in 2008 we can see a sudden fall in domestic extraction, caused by the closing of the *As Pontes* brown coal mine in 2007 (Pérez-Sindín López, 2015).

c) Spanish mineral dependency

Imports

Spain has clearly not enough mines to be a self-sufficient country regarding most commodities and it must rely on imports to be able to cover the internal needs.

In Figure 37 we can see the non-fuel mineral imports for the period 1995 to 2012. During this period, the main imported substances in mass terms were aluminium, copper, iron ore, manganese, phosphate rock and zinc. When converting those mass results into exergy replacement costs using the aforementioned methodology, we can see that it is mainly aluminium that stands out.

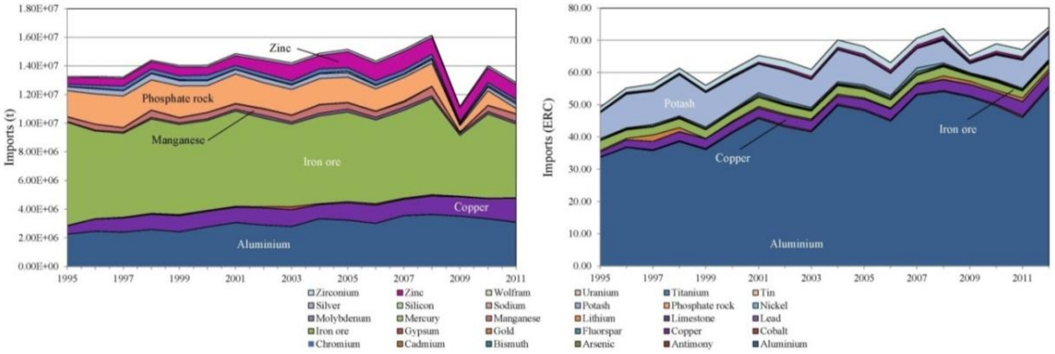

Figure 38. Spanish non-fuel mineral imports from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

In the case of non-fuel minerals, even if the tonnes imported are far less than the tonnes extracted, the exergy replacements costs for imports are higher than those for extraction. As explained before, this is the direct consequence of importing minerals with higher unit exergy costs (higher quality resources), such as aluminium or copper, while domestic extraction focuses on limestone and gypsum. Minerals with lower unit exergy costs, such as bulk construction minerals, are hardly traded due to its local abundance and lower prices.

We can also see that in 2008-2009 there is an important decrease that slightly recovers in the later years. This is mainly caused by the economic crisis and the overall decline of imports. This is not reflected so dramatically in terms of exergy replacement costs since imports of minerals with higher exergy replacement costs do not decrease as much as imports of minerals with lower ones.

As shown by these results, there is a reversed importance of exergy loss and tonnes, which is a direct consequence on the quality of the resources (the amount of energy needed for mining and also on the ore grade of the mines). For example, considering the total inputs (production and imports), in 2005 the domestic production of minerals (71.2%) was higher than the imports (28.8%) but as imports were mainly of scarce minerals, the exergy loss associated with such imports was higher (73.6%) compared to the one associated to domestic production (26.4%).

In the case of fossil fuel imports (Figure 38) we can see that they have gradually increased, experiencing some fluctuations over time. Despite domestic production, Spain still needs to import great quantities of fossil fuels. For example, in 2009, the degree for oil self-sufficiency in Spain was 0.18% and for natural gas it was 0.04% (CORES, 2009).

If we compare these imports with the domestic extraction we can see that it is roughly between 5 to 15 times higher in terms of exergy replacement costs depending on the year under consideration. From 2008 onwards, there has been a decrease of imports related to the economic crisis that is still affecting the country, reaching 1998 import levels in 2011.

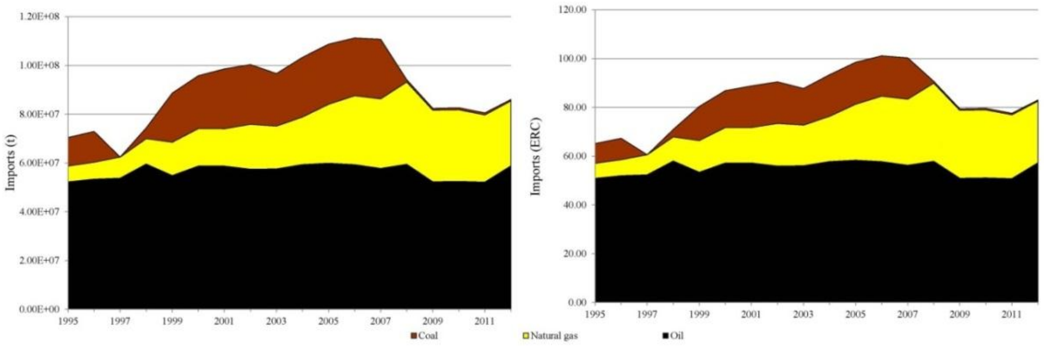

Figure 39. Spanish fossil fuels imports from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

As it can be seen, Spain is a very dependent country in the case of fossil fuels. In 2009, the degree for oil self-sufficiency in Spain was 0.18% and for natural gas it was 0.04% (CORES, 2009). The energy dependence or vulnerability to energy price shocks or energy supply disruptions is something vital for economies, since energy is a key variable for growth and competitiveness. Between 2006 and 2010 Spain had an average total import dependency of 80%, being the EU average 54%. Moreover, the gas and oil import dependency was 100% (Spooner et al., 2014).

Exports

Compared with domestic extraction and imports, exports are several orders of magnitude lower. Figure 39represents the non-fuel mineral exports from 1995 to 2012 both in tonnes and in exergy replacement costs. According to United States Geological Survey, Spain was in 2012 the third producer of gypsum at world level, after China and Iran, and the sixth producer of fluorspar along with Japan and Thailand (Gurmendi various years), among others.

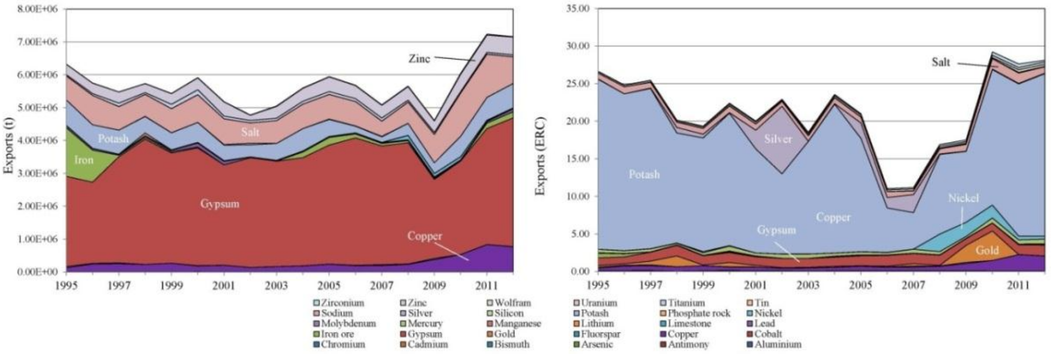

Figure 40. Spanish non-fuel mineral exports from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

During that period, the minerals exported were mainly gypsum, copper, salt, potash, zinc and iron. Overall, gypsum exports have always represented between 41 and 67% of the total exports, being one of the most important minerals for the Spanish export market. In 2012, 52.01% of the total mineral exports corresponded to gypsum, 10.72% to salt, 10.08% to copper, 9.85% to potash and 7.17% to zinc, the remaining 10,17% corresponded to other minerals such as magnesite, titanium or feldspar. When comparing the results in tonnes and in exergy replacement costs we can see again that the weight of potash changes drastically. Some minerals that could not be seen when representing the tonnes stand out when using exergy replacement costs, such as nickel, gold or silver. The exports expressed in tonnes and in exergy replacement costs follow the same trend until 2004, where exergy replacement costs decrease dramatically. This drastic change is produced by the decrease of potash exports. Due to the elevated unit exergy replacement costs of potash, a small increase or decrease in tonnes can represent a significant change in exergy replacement costs terms. From 2004 to 2009 the exports were almost halved and it is not until 2010 when the previous exports levels were regained again.

Spanish fossil fuel exports are represented in Figure 40. Fossil fuels exports are very low compared to imports, from 6 to 10 times lower and there have been many fluctuations over time. In 2001-2002 the total amount of exported fossil fuels decreased considerably as oil product exports were almost halved in that period of time.

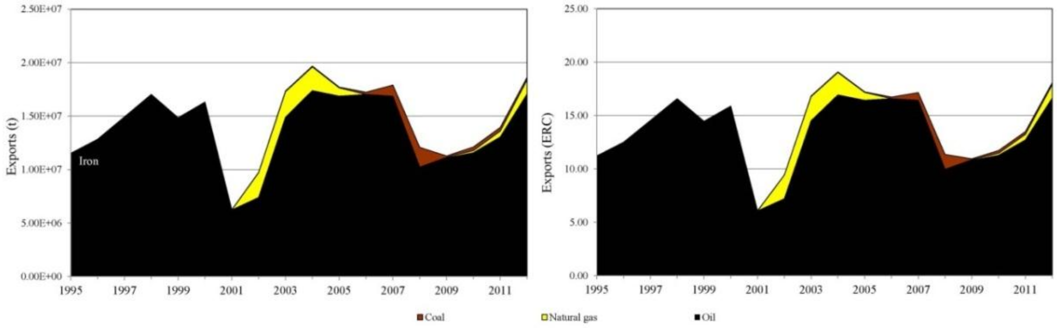

Figure 41. Spanish fossil fuel exports from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

Domestic Material Consumption (DMC)

With the domestic material consumption (DMC) over time we are analyzing the evolution of the annual amount of the material extracted, plus all the imports minus exports (Figure 41). In the case of a few minerals, such as salt, nickel and silver, the amounts exported some years where higher than the total sum of production plus imports, generating negative DMC numbers for these substances. This could be explained by a number of reasons such as exports of materials accumulated in previous years or by processing of tailings. In any case, these are only isolated situations that do not affect severely the overall results.

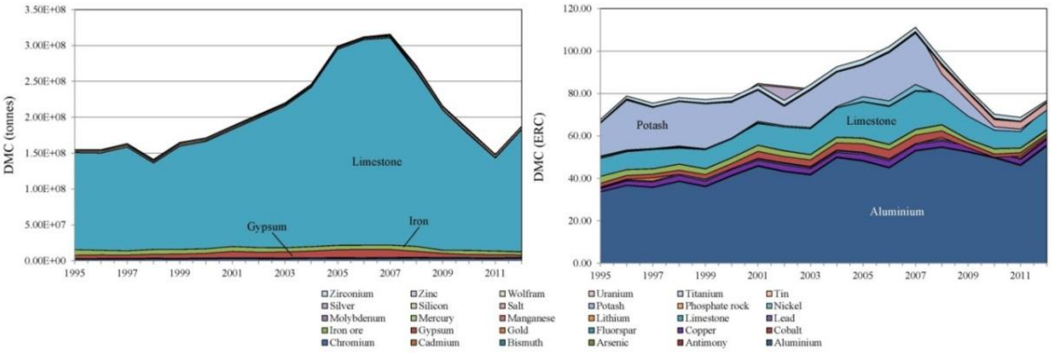

Figure 42. Spanish domestic material consumption (DMC) for non-fuel minerals from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

In the case of non-fuel minerals we can see that DMC expressed in tonnes does not exactly follow the same tendency as exergy replacement costs since from 1995 to 2004 the latter has a less pronounced slope. Minerals that are imported and a small amount of those that are extracted have higher exergy replacement costs, since they are usually scarcer minerals. In tonnes, we can see that in general limestone was the most consumed commodity followed by iron and gypsum. In exergy replacement costs we can see that the main substances consumed are aluminium, potash and limestone.

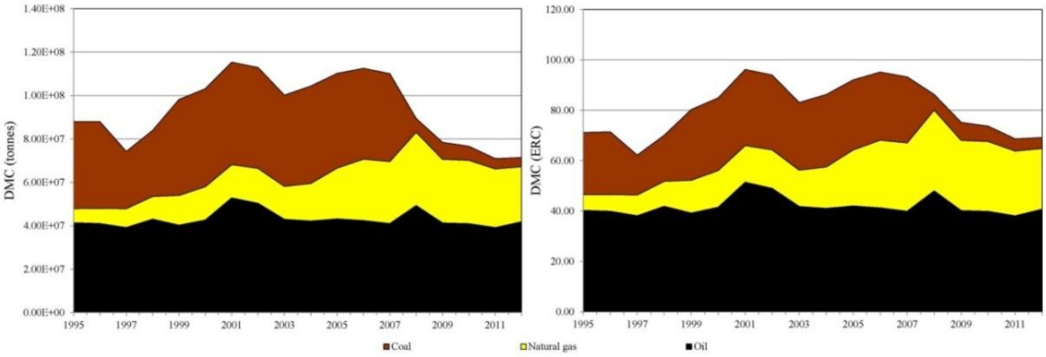

Figure 43. Spanish domestic material consumption (DMC) for fossil fuels from 1995 to 2012 expressed in tonnes (left) and in exergy replacement costs (right).

In the case of fossil fuels (Figure 42) we can observe how important fossil fuel use is for the economy as, we should not forget that the vast majority of the fossil fuels used in Spain are imported.

The impact on the Spanish natural resource depletion is higher than expected if we look at the exergy loss than if we were just taking into consideration this loss in mass terms. Both in the case of fossil fuels and non-fuel minerals we can also see the influence of the economic crisis that started in 2008, where an important decrease of imports and domestic extraction took place.

5.7.2. MATERIAL FLOW ANALYSIS FOR EUROPE. AN EXERGOECOLOGICAL APPROACH.

Even if it is interesting to have a general overview of the whole European Union situation, we can also analyze the data disaggregated by countries. Domestic extraction, imports, exports and DMC data for fossil fuels plus non-fuel minerals of selected European countries are represented in Figure 43.

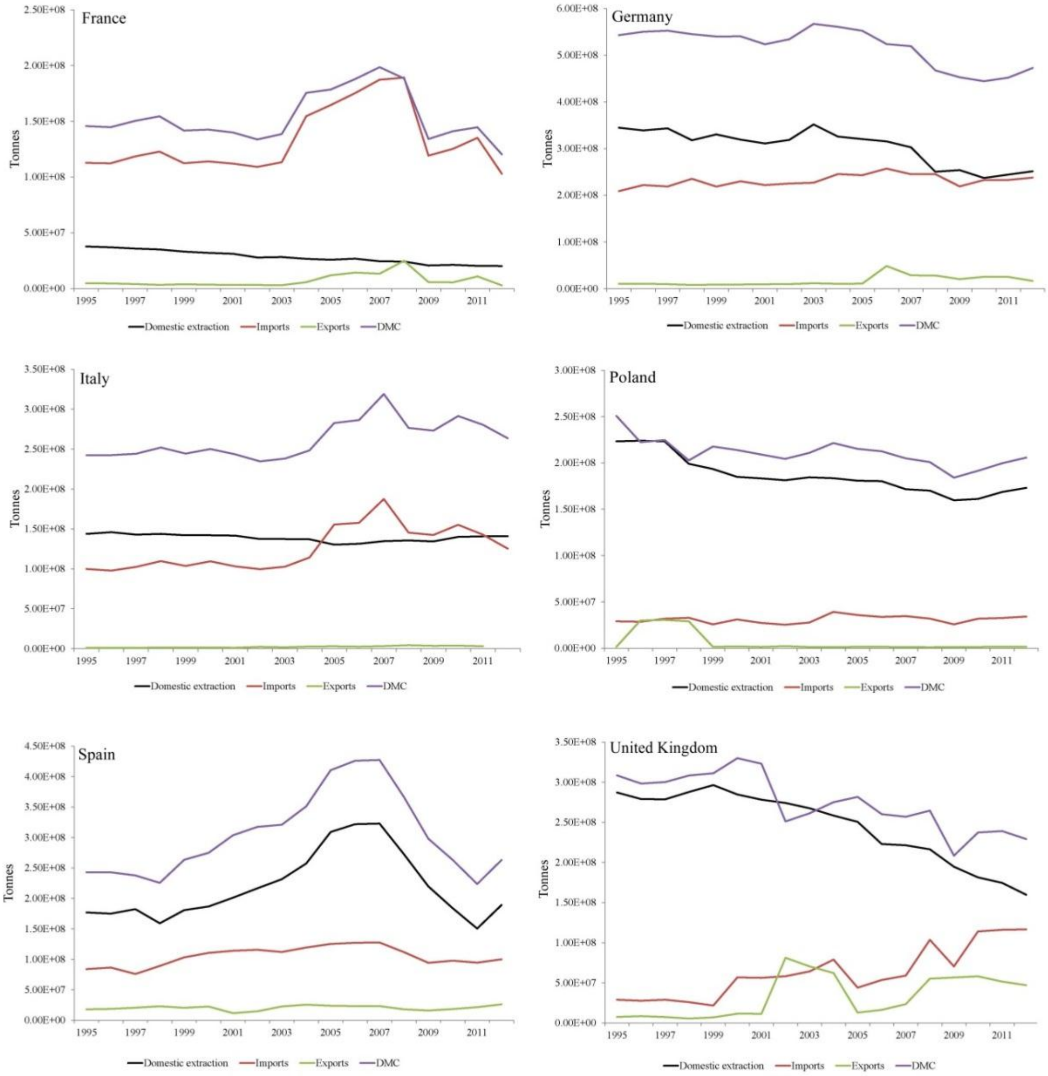

Figure 44. Domestic extraction, imports, exports and DMC in tonnes for selected European countries from 1995 to 2012.

Of the selected countries, France is the only one whose total imports are much higher than the domestic extraction. The main reason is the fossil fuel imports, which accounted for an average of 80% of the total imports each year. Germany and Italy have similar values of domestic extraction and imports, while Spain, United Kingdom and Poland rely more on internal production.

6. RESULTS

A summary of all the results obtained in the published papers, as well as the initial objectives of each paper and the main conclusions are presented in the following table (Table 23).

Table 23. Summary of the published results.

Objectives	**Paper**	**Conclusions**
Refine and improve methodology.	Calvo, G., Valero, A., Mudd, G. **Energy intensity factors in gold, copper, lead and zinc mining projects** (*Under preparation).*	Additional data of exergy replacement costs were calculated using real data of energy use in mines.
Create a link between Ecological economics and Physical Geonomics.	Valero, A., Carpintero, Ó, Valero, A. Calvo, G. (2014). **How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study**. *Ecological Indicators*, 46, 548-559.	New mineral prices were obtained incorporating exergy replacement costs to the market prices.
Global resource efficiency indicators.	Valero, A., Valero, A., Calvo, G. (2015). **Using thermodynamics to improve the resource efficiency indicator GDP/DMC.** *Resources, Conservation and Recycling*, 94, 110-117.	A new global indicator was proposed to measure resource efficiency that incorporates exergy replacement costs: DMD/GDP.
Validate the methodology with different case studies: • Spain • European Union (EU-28) • Colombia	Calvo, G., Valero, A., Valero, A., Carpintero, Ó. (2015). **An exergoecological analysis of the mineral economy in Spain.** *Energy*, 88, 2-8. Calvo, G., Valero, A., Valero, A, (2016). **Material flow analysis for Europe. An exergoecological approach.** *Ecological Indicators*, 60, 603-610. Calvo, G., Valero, A., Carmona, L.G., Whiting, K. **Physical assessment of the mineral capital of a nation: the case of an importing and an exporting country.** (*Sent to Resources - ISSN 2079-9276).*	The Physical Geonomics model was applied at a macro-scale in three different regions, observing a high external dependency on natural resources supply for Spain and Europe. Additionally, it was observed that exporting countries, in this case Colombia, are underselling their resources as the monetary gain resulting from the extractive sector does not compensate the loss of mineral resources.

7. CONCLUSIONS

In this section a summary and the main conclusions that have been obtained in the development process of this PhD Dissertation will be listed. Subsequently, the main contributions and the scientific publications derived from this research will be presented. Finally, perspectives for future research will be proposed.

7.1. SUMMARY

Natural resource extraction and consumption rate has been continuously increasing over time, almost exponentially, in the last few decades. National and international entities are increasingly focusing on this issue, as studies about both availability and criticality are becoming more and more important to improve natural resource management. For this reason, it is fundamental to have the best possible tools, objective and rigorous, to properly account for the use of resources.

Using Physical Geonomics, mineral extraction, and specifically mineral dispersion, can be assessed through exergy, a property derived from the Second Law of Thermodynamics. The main advantage of this approach when compared to other methodologies is that it allows to obtain more accurate information on mineral dispersion as exergy is a property that takes into account not only quantity but also quality of the materials analyzed. Additionally, it is a variable not linked to monetary variations or mineral prices.

This PhD Dissertation can be divided into four different parts and tasks. The first part has consisted on improving the existing methodology using real data on energy consumption from different mining industries. In the second part a resource efficiency indicator has been developed to better evaluate mineral depletion and to provide more accurate tools for policy making processes. The third part has helped to link Physical Geonomics and Ecological Economics, incorporating in the mineral prices the exergy replacement costs of each substance. Last, Physical Geonomics has been applied at macro-scale using Spain, Europe (EU-28) and Colombia as case studies.

An analysis of the energy use and energy intensity in different mining projects has been carried out starting from sustainability and annual reports from different companies. Using the available information of fossil fuel and electricity consumption over the years, as well as changes in ore grade and ore mined and milled, several energy intensity factors have been calculated. Additionally, an analysis of the energy use as a function of the ore grade has been carried out. The main goal was to empirically demonstrate that the relationship between ore grade and energy consumption follows an exponential tendency, and although a relationship between these two factors can be observed in the data presented in this dissertation, the results do not confirm an exponential trend. In any case, many factors come into play, as the way each mine reports their data or the fact that only data from 40 mines were used; therefore more studies should be carried out regarding this issue.

The energy use in mines is strongly dependent on the ore grade and also on the type of process used in the mine. As a general rule, a decrease in ore grade is associated with an increase in energy use, so it can be determined that ore grade is one of the main factors that can influence the use of energy in a mine. This has been demonstrated for the case of copper, as over time ore grade is decreasing, while energy consumption and material extracted is increasing.

New values for exergy replacement costs have been calculated, using real data, for copper, gold and zinc. These new values are only based on real information and are an improvement with respect to the previous data, only based on theoretical use of energy. Additionally, exergy replacement costs for gallium, germanium and indium have been calculated using the energy information based on their concentration in the main ore of which they are extracted. Comparing all these new values, it can be stated that the minerals that appear less concentrated in the mines have higher exergy replacement costs than those that are more concentrated.

Once the methodology has been improved and refined, new aspects can be developed in the road to sustainability. A global resource efficiency indicator has been proposed in this regard, GDP/DMD (Gross Domestic Product divided by Domestic Material Dispersion), indicator that takes into account not only Domestic Material Consumption (extraction, imports and exports) but also recycling. Incorporating the quality of the minerals and also the important role of recycling in the indicator, can simplify and clarify the information available. With this new indicator we can have a better and more accurate assessment of mineral depletion and it can be used to better decisions and more effective actions in the policy making process. Still, even if this new proposed indicator can be used as an overall indicator, it is important to group certain materials into different categories and not use it only as an aggregated indicator. The categories should be related to the different critical aspects of natural resources (supply risk, economic importance, environmental risk, etc.) therefore providing more useful and complementary information.

Including tools derived from Physical Geonomics within Ecological Economics can be extremely helpful to evaluate natural resource efficiency use. Once the exergy replacement costs are incorporated in the calculations, another aspect that can be analyzed is the mineral market prices and the monetary loss associated to mineral extraction and depletion. Using current mineral market prices, a new mineral price has been estimated taking into account the exergy replacement costs for each one of the minerals in the valuation process. This way, the new mineral prices take into account scarcity and not only economic factors. The results show that certain minerals should have prices 27 times higher as an average than the current ones, while the prices of other minerals does not change substantially when incorporating the exergy replacement costs in the calculations. This allows seeing the distance between situations in which resources are treated as ordinary goods whose price is dependent on production costs and situations in which they are treated as physical assets that needs to be replaced to meet the objective of sustainable development.

Several case studies have been developed to apply the aforementioned methodology at the macro-scale. For this endeavor, Spain, Europe (EU-28) and Colombia have been chosen as examples of regions where mineral extraction and trade is substantial. Historically, Spain has always been a territory rich in mineral resources with an important mining sector. Spanish mineral extraction and mineral trade has been studied in depth, as well as the monetary loss associated to the mineral depletion. Using data on existing reserves, the Spanish mineral depletion degree in the last century associated to mineral extraction is 44% as an average. While the domestic extraction heavily relies on the changes on the internal demand, as demonstrated by the housing bubble influence, imports play a major role in the economy. Spain is a very dependent country on external supply and all imports and materials extracted are consumed within the borders of the country. The same situation can be observed in all the member states of the European Union, a territory highly dependent on imports and with an important trade deficit regarding non-fuel minerals and fossil fuels. Carrying out an economic analysis related to analyze the monetary loss associated to mineral depletion, especially in the case of countries that mainly export their goods, it can be inferred that these countries and usually underselling their natural resources, as the economic value they get for their exports does not compensate the loss of mineral patrimony. Such is the case of Colombia, a country whose mining sector contributed $38 billion USD in the GDP during the year 2009. It may seem a reasonable estimate but when analyzing the costs needed to return the minerals to its original conditions, this initial number proves to be 30 to 50% lower than the monetary costs associated with the mineral loss caused.

As demonstrated by all the case studies, carrying out a conventional material flow analysis to study mineral depletion is not enough, as material flow analysis and conventional indicators are usually related to monetary valuation and usually put together substances that are very different from each other. To complement this approach and to obtain more realistic and accurate values, an exergy approach is needed, as it places focus on the quality of the minerals and can help having a better overall picture of mineral depletion.

Another thing that stands out after carrying those analyses is the lack of reliable and detailed information regarding mineral extraction, imports, exports and recycling. And the same situation can be extrapolated to energy use in mining projects. There are several databases and several mining companies that usually make their reports available to the general public, but these sources are typically incomplete or the information cannot always be used for comparative purposes as the information is not reported in the same way. Especially striking is the case of recycling rates of metals, again there are some aggregated reports about this issue but it is very complicated to obtain realistic values for each separate country. To have a better assessment of the mineral depletion and to improve sustainability, it is fundamental to have good and solid values. There are several initiatives, such as the Global Transparency Initiative (GTI) or the Global Reporting Initiative (GRI) that encourage such behaviors, but a lot of work needs to be done in this direction.

7.2. CONTRIBUTIONS

The main contribution of this PhD Dissertation is the verification and improvement of the Physical Geonomics methodology, using real information on energy consumption for selected metallic minerals to obtain more accurate exergy replacement costs data, and applying these results to several case studies. The specific contributions are outlined next.

1. With all the information obtained from Chapter 2 it can be demonstrated that mineral depletion and decreasing ore grades is no longer a theoretical issue but a global reality caused by the increasing consumption of raw materials. And, as far as we know, the exergy analysis of the 40 most economically important metallic mines at global level carried out in this dissertation is the first approach of its kind.

    a. The main contribution of this chapter has been validating and improving the Physical Geonomics theory, comparing theoretical data of energy use in the mining industry with empirical data for copper, gold and zinc. Resulting from this analysis, new and more accurate values of exergy replacement costs for copper, gold and zinc have been calculated.

   b. Additionally, an analysis of the energy intensity use in mining over time has been conducted, regarding specifically electricity and diesel use, as a function of the ore grade. Besides, the influence of the mining process or mine type in the energy use has been studied.

   c. Starting from the information related to copper mines, the changes in the ore grade at global level over time have been analyzed as well as its relationship with the energy consumption.

   d. The last contribution of Chapter 2 is the estimation of the exergy replacement costs of gallium, germanium and indium, substances that are critical for renewable technologies and whose exergy replacement costs had not yet been calculated before.

   e. With the results obtain in this chapter a scientific paper is being prepared, provisionally entitled: *Energy intensity factors in gold, copper, lead and zinc mining projects.*

2. As the problem of mineral depletion is a global reality, the society needs indicators that can properly assess this issue. Therefore the main contribution of **Chapter 3** is the proposal of a new global indicator to evaluate resource efficiency to the European Commission based on a thermodynamic approach: GDP/DMD.

   a. This proposed indicator (GDP/DMD) can be used to properly assess mineral dispersion, incorporating exergy replacement costs (ERC) in the calculations and this was corroborated using Spain as a case study.

   b. The information presented in this chapter resulted in the publication of a scientific paper (**Paper I**): *Using thermodynamics to improve the resource efficiency indicator GDP/DMC.*

3. The main contribution of **Chapter 4** is converting exergy replacement costs into monetary costs, obtaining theoretical mineral market prices that include exergy replacement costs in the calculation system.

   a. Once the exergy replacement costs are incorporated in the market mineral prices it has been stated that some are 10 to 80 times higher, being the average of these new market prices 27 times higher than the current market prices for the year 2009. This approach allows seeing the differences between situations where resources are treated as ordinary goods and situations where they are treated as physical assets that need to be replaced.

b. The information presented in this chapter resulted in the publication of a scientific paper (**Paper II**): *How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study*.

4. In **Chapter 5** the Physical Geonomics theory has been applied for the first time at macro-scale using three different case studies: Spain, Europe (EU-28) and Colombia, to evaluate mineral depletion in each region. This analysis has been carried out using Sankey diagrams, expressed both in tonnes and in exergy replacement costs, to observe the flows of natural resources, non-fuel minerals and fossil fuels, within a region.

   a. The first contribution is the analysis of mineral extraction in Spain throughout the 20th century, both for non-fuel minerals and fossil fuels. The estimation of the depletion degree of Spanish mineral reserves, and the impacts of imports, exports and consumption. This resulted in the publication of a scientific paper (**Paper III**): *An exergoecological analysis of the mineral economy in Spain.*

   b. The second contribution of Chapter 5 is carrying out a material flow analysis for Europe (EU-28) from 1995 to 2012 using an exergoecological approach, taking into account domestic extraction, imports, exports, consumption and recycling. Analyzing the trade deficit, self-sufficiency and the foreign dependency using exergy replacement costs. This resulted in the publication of a scientific paper (**Paper IV**): *Material flow analysis for Europe: an exergoecological approach.*

   c. The last contribution has been assessing in monetary terms the loss associated with mineral depletion for Spain and Colombia, and comparing this loss with the GDP generated by the mineral sector. These results are shown in the paper *Physical assessment of the mineral capital of a nation: the case of an importing and an exporting country*, pending from publishing.

7.3. SCIENTIFIC PUBLICATIONS

The work developed in this dissertation has resulted in 4 papers published in JCR journals; the additional information obtained has given rise to two more papers, one is already being reviewed by a journal and the other is currently under preparation. All these contributions are listed in Table 24.

Moreover, a total of 7 contributions have been presented to national and international conferences, and one of them, *An exergoecological analysis of the mineral economy in Spain*, presented in ECOS 2014, received the Best paper award. All these contributions are listed in Table 25.

Additionally, a dissemination paper was published in the newsletter of the Aragón College of Mining Engineers.

Author: Calvo, Guiomar
Title: Agotamiento de los recursos minerales de España *(Depletion of Spanish mineral resources)*
Newsletter: Boletín Informativo Colegio Oficial de Ingenieros Técnicos de Minas y de Grado en Minas y Energía de Aragón. Número 24.
Date: June 2014.

Finally, a book chapter was also written as a result of this work.

Authors: Valero, Alicia; Valero, Antonio; Calvo, Guiomar.
Title: Agotamiento del capital mineral de la Tierra (*Depletion of the Earth's mineral capital)*.
Book: Los inciertos pasos desde aquí hasta allá: Alternativas socioecológicas y transiciones postcapitalistas (*Uncertain steps from here to there: socio-ecological alternatives and post-capitalist transitions).*
Date: 2015.
Editorial: Editorial Universidad de Granada.
Editors: Riechmann, J., Carpintero, Ó and Matarán, A.
ISBN: 978-84-338-5715-6.

Table 24. Main articles derived from this thesis.

Work	Title	Authors	Journal title	DOI	Impact factor	Status
1	How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study.	Valero, Antonio; Carpintero, Óscar; Valero, Alicia and **Calvo, Guiomar**.	*Ecological Indicators*	http://dx.doi.org/10.1016/j.ecolind.2014.07.021	3.444	Published (2014)
2	Using thermodynamics to improve the resource efficiency indicator GDP/DMC.	Valero, Alicia; Valero, Antonio and **Calvo, Guiomar**.	*Resources, Conservation and Recycling*	http://dx.doi.org/10.1016/j.resconrec.2014.12.001	2.564	Published (2015)
3	An exergoecological analysis of the mineral economy in Spain.	**Calvo, Guiomar**; Valero, Alicia; Valero, Antonio and Carpintero, Óscar.	*Energy*	http://dx.doi.org/10.1016/j.energy.2015.01.083	4.844	Published (2015)
4	Material flow analysis for Europe. An exergoecological approach.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	*Ecological Indicators*	http://dx.doi.org/10.1016/j.ecolind.2015.08.005	3.444	Published (2016)
5	Physical assessment of the mineral capital of a nation: the case of an importing and an exporting country.	**Calvo, Guiomar;** Valero, Alicia; Carmona, Luis Gabriel and Whiting, Kai	*Resources ISSN 2079-9276*	-	-	*Sent to journal (09/2015)*
6	Energy intensity factors in gold, copper, lead and zinc mining projects.	**Calvo, Guiomar;** Valero, Alicia; Mudd, Gavin	-	-	-	*Under preparation*

Table 25. Contributions in national and international conferences.
(*) Best paper award.

Work	Title	Authors	Conference	Date and place
1	Detalles históricos sobre la producción de wolframio y estaño en España.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	XIII Congreso Internacional sobre Patrimonio Geológico y Minero.	Manresa, Spain. September 2012.
2	Is the lead indicator GDP/DMC preliminarily proposed by the European Commission an appropriate indicator to measure resource efficiency?	Valero, Antonio; Valero, Alicia and **Calvo, Guiomar**.	Fourth Aachen International mining Symposia (AIMS).	Aachen, Germany. May 2013.
3	How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study.	Valero, Antonio; Valero, Alicia; **Calvo, Guiomar** and Carpintero, Óscar.	10th biennal conference of the European Society for Ecological Economics (ESEE).	Lille, France. June 2013.
4	An exergoecological analysis of the mineral economy in Spain. (*)	Valero, Antonio; Valero, Alicia; **Calvo, Guiomar** and Carpintero, Óscar.	27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental impact of Energy Systems (ECOS).	Turku, Finland. June, 2014.
5	Sankey and Grassmann diagrams for mineral trade in the EU-28.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	7th International Exergy, Energy and Environment Symposium (IEEES).	Valenciennes, France. April, 2015.
6	Exergy as a resource efficiency indicator for industries.	Valero, Alicia; Valdés, Marianela and **Calvo, Guiomar**.	28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS).	Pau, France. June-July, 2015.
7	Material flow analysis for Europe. A thermodynamic approach.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	8th Conference of the International Society for Industrial Ecology (ISIE).	Guildford, United Kingdom. July, 2015.

7.4. PERSPECTIVES

Considering the results and conclusions obtained from the work developed in this dissertation, further opportunities of research have been identified.

In this PhD thesis the exergy replacement costs of 6 commodities were obtained, but only half of them were based on data on real energy consumption as a function of ore grade. It is fundamental to have empirical data of other substances to improve the methodology and have the most accurate and reliable data as possible of the exergy replacement costs of each mineral. Therefore, the calculation and refining of exergy replacement costs should be done for other substances using real information.

Additionally, as only data coming from 40 mines was used to study the empirical relationship between energy consumption and ore grade, to verify if they have an exponential relationship, more studies should be made including more mines and more substances.

So far, the material flow analysis has been carried out only at a macro-scale level, using the mineral trade of several countries and territories as different case studies. This same analysis could be carried out at micro-scale level, analyzing electronic devices, and in general new technologies such as renewables, and the minerals needed to produce them.

Another complementary issue could be including Physical Geonomics in the traditional Life Cycle Analysis (LCA). Usually LCA usually uses a cradle-to-grave approach and introducing exergy replacement costs in the methodology, adding the grave-to-cradle approach, could help to better assess the whole picture.

To cross over from the theoretical to the practical level and to improve the management of mineral resources, it is of vital importance that all nations account for their loss of mineral capital properly. A good starting point is the System of Environmental-Economic Accounts (SEEA) proposed by the United Nations. However, the SEEA should be further developed into a Global System of Environmental-Thermo-Economic Accounts (SETEA), where the unit of measure instead of tonnes or monetary units is in terms of exergy replacement costs, thereby accounting for the depletion of minerals. For this reason, starting from SEEA, a new, stronger and practical infrastructure can be developed so as to improve the management of limited and critical resources on Earth.

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9. ANNEXES

9.1. JUSTIFICATION OF THE CONTRIBUTION OF THE PHD STUDENT

The PhD student, Ms. Guiomar Calvo Sevillano was in charge of making the review of the existing literature, compiling the mineral extraction and trade information using several databases, carrying out the calculations and performing the analysis of the results of the previously presented publications. Everything was done under the supervision of the other authors of the papers.

9.2. COMPLETE REFERENCES OF THE PAPERS

Complete references of the articles included in this dissertation are listed below, in chronological order, along with the impact factors and subject categories of each of the journals in which they were published.

1. Valero, A., Carpintero, Ó, Valero, A. Calvo, G. (2014). **How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study**. *Ecological Indicators*, 46, 548-559.

Ecological Indicators impact factor: 3.444 © Thomson Reuters Journal Citation Reports 2015.
Subject category (journal ranking): Environmental Sciences (Q1; 34/221).

2. Valero, A., Valero, A., Calvo, G. (2015). **Using thermodynamics to improve the resource efficiency indicator GDP/DMC.** *Resources, Conservation and Recycling*, 94, 110-117.

    Resources, Conservation and Recycling impact factor: 2.564 © Thomson Reuters Journal Citation Reports 2015.
    Subject categories (journal ranking): Environmental Engineering (Q2; 17/47), Environmental Sciences (Q2; 71/223).

3. Calvo, G., Valero, A., Valero, A., Carpintero, Ó. (2015). **An exergoecological analysis of the mineral economy in Spain.** *Energy*, 88, 2-8.
    Energy impact factor: 4.844 © Thomson Reuters Journal Citation Reports 2015.
    Subject categories (journal ranking): Energy&Fuels (Q1; 12/88), Thermodynamics (Q1; 2/55).

4. Calvo, G., Valero, A., Valero, A, (2016). **Material flow analysis for Europe. An exergoecological approach.** *Ecological Indicators*, 60, 603-610.

    Ecological Indicators impact factor: 3.444 © Thomson Reuters Journal Citation Reports 2015.
    Subject category (journal ranking): Environmental Sciences (Q1; 34/221).

CONCLUSIONES

En esta sección se van a enumerar los principales resultados que se han obtenido durante la realización de esta tesis doctoral; del mismo modo también se incluye un apartado donde se van a comentar las contribuciones y los artículos derivados de esta tesis doctoral, las futuras líneas de investigación y las perspectivas.

RESUMEN

La velocidad de extracción de recursos naturales y la tasa de consumo ha crecido de forma continuada a lo largo del tiempo, proceso que se ha acelerado, llegando a mostrar incluso tendencias exponenciales, en las últimas décadas. Distintas entidades nacionales e internacionales están centrando cada vez más sus esfuerzos en esta cuestión, al tiempo que van surgiendo informes cuya preocupación versa en torno a la disponibilidad y criticidad de los materiales, con el fin de mejorar la gestión de los recursos naturales. Por este motivo, y porque los recursos naturales son una base fundamental para la economía de un país, es imprescindible contar con herramientas que sean objetivas y rigurosas para poder evaluar de forma apropiada dichos recursos.

Empleando la Geonomía Física se puede evaluar la extracción mineral, y concretamente la dispersión mineral, mediante el uso de la exergía, una propiedad derivada de la Segunda Ley de la Termodinámica. La principal ventaja de este enfoque, si se compara con otras metodologías, es que permite obtener información más precisa sobre la dispersión mineral, ya que la exergía es una propiedad que tiene en cuenta no solo la cantidad sino también la calidad de los materiales, siendo al mismo tiempo una variable que no está vinculada a fluctuaciones económicas ni al precio de mercado de los minerales.

Esta tesis doctoral está dividida en cuatro partes y tareas claramente diferenciadas. La primera tarea que se ha desarrollado está centrada en mejorar la metodología existente, empleando para ello información del consumo real de energía y materiales en distintas industrias mineras. En la segunda parte se ha desarrollado un indicador con el fin de que pueda ser empleado para evaluar la eficiencia en el uso de recursos, específicamente en cuanto a la dispersión de minerales. Dicho indicador tiene como fin proveer de herramientas más precisas y objetivas a los encargados de elaborar políticas relativas a la eficiencia en el uso de recursos naturales. La tercera tarea ha consistido en relacionar la Geonomía Física y la Economía Ecológica, incorporando para ello en el precio de mercado de los minerales los costes exergéticos de reposición de cada sustancia. Por último, la Geonomía Física ha sido aplicada por primera vez a escala macroscópica, utilizando España, Europa (EU-28) y Colombia como casos de estudio.

En primer lugar se ha llevado a cabo un análisis del consumo energético en diversos proyectos mineros a partir de la información procedente de informes de sostenibilidad e informes anuales de distintas compañías mineras. Empleando la información anual del consumo de electricidad y de combustibles fósiles, junto con las cantidades de material extraído y molido, y con los datos de variación anual de la ley de mineral, se han calculado distintos factores relacionados con la intensidad en el uso de energía. Asimismo, se ha llevado a cabo un estudio de la evolución del consumo energético en función de la ley del mineral. El principal objetivo ha sido intentar demostrar empíricamente que la relación existente entre la ley del mineral y el consumo energético es de tipo exponencial, pero aunque sí se aprecia una cierta relación entre los dos factores en los datos recopilados, no se han podido obtener resultados concluyentes. En cualquier caso, muchos otros factores entran en juego en el caso del consumo energético de una mina; también hay que tener en cuenta que no todas las empresas mineras hacen los informes siguiendo los mismos criterios y que solamente se han tenido en cuenta 40 minas para este estudio. Es, por tanto, necesario ampliar esta información y abarcar un mayor campo de estudio para poder comprobar si realmente esta tendencia exponencial se puede confirmar.

El uso de energía en las minas depende de la ley del mineral pero también del tipo de procesado existente. Por norma general, una disminución de la ley del mineral está asociada con un aumento en el consumo energético, por lo que se puede concluir que la ley del mineral sí es un factor fundamental en cuanto a ese uso. Esto se ha podido demostrar para el caso del cobre, ya que a lo largo del tiempo la ley del mineral ha ido disminuyendo mientras que el material removido y el consumo energético asociado a la extracción han ido aumentando.

Se han calculado nuevos valores de los costes de reposición para el cobre, el oro y el zinc partiendo de datos empíricos. Estos nuevos valores están basados en datos reales y suponen una gran mejoría respecto a los datos de partida, calculados únicamente de forma teórica. Adicionalmente, se han calculado los costes teóricos de reposición para el galio, germanio e indio, tomando como base de partida su concentración en la mena principal de la que se extraen. Comparando estos nuevos valores de costes exergéticos de reposición con los ya existentes para otras sustancias, se puede apreciar que los minerales con menores concentraciones en las minas son aquellos que tienen mayores costes exergéticos de reposición.

Una vez se ha procedido a la mejora de la metodología, se han desarrollado nuevos aspectos. Se ha desarrollado y propuesto un nuevo indicador en relación con el uso sostenible de los recursos basado en el Producto Interior Bruto (GDP) y la Dispersión Doméstica de Materiales (DMD), denominado GDP/DMD. Este nuevo indicador no solo tiene en cuenta el consumo de materiales (extracción, importaciones y exportaciones) sino que también incluye el reciclado. Además, usando la exergía, se está incorporando en el indicador la calidad de los minerales, y añadiendo la información del reciclado, se pueden obtener resultados más claros. Con este nuevo indicador se puede tener una visión mejor y más precisa de la dispersión mineral y puede ser empleado para emprender acciones más efectivas a la hora de elaborar políticas relacionadas con el uso eficiente de los recursos. Aun así, aunque este indicador puede ser empleado como un indicador general, es importante poder agrupar las sustancias en distintas categorías para poder obtener así un indicador más desagregado. Estas categorías deberían estar relacionadas con los distintos aspectos que son críticos para los recursos naturales, como pueden ser la seguridad de suministro, su importancia económica, riesgo medioambiental, etc., pudiendo así proporcionar información complementaria.

Incluir herramientas derivadas de la Geonomía Física dentro de la Economía Ecológica puede ser extremadamente útil para evaluar la eficiencia en el uso de recursos naturales. Una vez los costes exergéticos de reposición se incorporan en el método de cálculo, otro factor que se puede analizar es el precio de mercado de los minerales y el coste monetario asociado a la extracción y dispersión mineral. Partiendo de los precios de mercado de los minerales, se ha calculado un nuevo valor para cada uno de los minerales teniendo en cuenta los costes de reposición en la valoración final, de forma que este nuevo valor de cada mineral tiene en cuenta no solo factores económicos sino también factores relacionados con su escasez y su criticidad. Los resultados obtenidos muestran que ciertos minerales deberían tener un valor medio 27 veces superior al actual aunque en el caso de otros el precio se mantendría aproximadamente dentro de los mismos valores aun teniendo en cuenta los costes asociados a su reposición. Eso permite ver la diferencia entre dos situaciones, una en la que los recursos son tratados como si fueran bienes cuyo precio solo depende de los costes de producción y otra situación en la que son tratados como activos que deben ser reemplazados para cumplir con el objetivo de alcanzar un desarrollo sostenible.

A continuación se han desarrollado distintos casos de estudio aplicando la Geonomía Física a distintos territorios. Para este fin se han seleccionado España, Europa (EU-28) y Colombia como ejemplos de zonas donde la extracción mineral y el comercio es relativamente considerable. Históricamente, España ha sido un país rico en recursos minerales con un importante sector minero. Tanto la extracción y comercio mineral en España como la pérdida monetaria asociada a esta dispersión mineral han sido estudiados en profundidad. Partiendo de los datos de reservas existentes, el grado de agotamiento de los recursos minerales de España es de un 44% como media. A pesar de que la extracción doméstica está influenciada fuertemente por las necesidades locales, tal y como queda demostrado por la influencia de la burbuja inmobiliaria en la extracción de materiales empleados en el sector de la construcción, son las importaciones de recursos minerales las que juegan un papel más relevante en la economía. España es un territorio muy dependiente del exterior para cubrir sus necesidades y la gran mayoría de los materiales extraídos e importados se consume dentro del propio territorio. Esta misma situación se puede observar a gran escala en la práctica totalidad de los países pertenecientes a la Unión Europea, una región muy dependiente de las importaciones y con un déficit comercial importante en lo relativo a combustibles fósiles y minerales. Los análisis económicos que se han llevado a cabo para ver la relación entre la pérdida de capital mineral y la pérdida monetaria asociada han puesto en evidencia que los países que basan su economía principalmente en la exportación de materiales están vendiendo sus recursos a un precio menor del que deberían, ya que el valor que obtienen por el material que exportan no compensa la pérdida de patrimonio mineral. Esto ha quedado demostrado para el caso de Colombia, un país cuyo sector minero en 2009 generó 38 miles de millones de dólares. A primera vista puede parecer una cifra razonable, pero al incorporar en los cálculos los costes necesarios para reponer los recursos perdidos, esta cifra resulta ser entre un 30 y un 50% menor de la que debería tener.

Tal y como se ha demostrado a través de todos los casos de estudio, llevar a cabo un análisis de flujo de materiales de forma convencional puede dar una idea aproximada pero que no es suficiente, ya que por norma general este tipo de análisis se basa en factores económicos y analiza conjuntamente sustancias que son muy diferentes unas de otras. Para complementar este tipo de análisis y para obtener información más realista y precisa, se puede aplicar el análisis exergético, dado que pone énfasis en la calidad de los minerales y puede así dar una imagen más práctica de la dispersión mineral.

Otro de los aspectos que llama la atención es la falta de información fiable y detallada sobre la extracción mineral y también sobre las importaciones, exportaciones y reciclado de estos materiales. Esta misma falta de información también puede ser extrapolada al sector minero y al uso de energía por sectores. Existen múltiples bases de datos accesibles al público general pero habitualmente estas bases de datos están incompletas, no coinciden entre ellas o la información que reflejan no siempre puede ser empleada para llevar a cabo estudios comparativos ya que no está compilada de la misma forma. Especialmente llamativo es el caso del reciclado de metales, ya que existen distintos informes sobre esta cuestión pero en muchas ocasiones son informes complicados de obtener y cuya información está muy agregada, por lo que es difícil conseguir cifras de reciclado para cada país en concreto. Para poder llevar a cabo un mejor análisis de la dispersión de los recursos minerales es fundamental disponer de datos de partida sólidos y fiables, y aunque también existen distintas iniciativas que promueven la transparencia de dichos sectores, como la Iniciativa de

Transparencia Global (GTI) o la Iniciativa del Reporte Global (GRI) que fomentan estas buenas prácticas, todavía es necesario llevar a cabo mucho trabajo en esta dirección dadas las lagunas existentes.

CONTRIBUCIONES

La principal contribución de esta tesis doctoral es la verificación y mejora de la Geonomía Física, empleando para ello información real del consumo de energía en distintas minas metálicas para obtener valores más precisos de los costes exergéticos de reposición. Al mismo tiempo, esta tesis supone la primera vez que se aplica dicha metodología a escala macroscópica mediante el desarrollo de distintos castos de estudio.

A continuación se van a presentar las principales contribuciones de esta tesis doctoral según su orden de aparición en el texto.

1. Con la información obtenida en el **Capítulo 2** se ha demostrado que el agotamiento de los minerales y la disminución de la ley del mineral ya no es simplemente una cuestión teórica sino una realidad global causada por el aumento del consumo de materiales. En este estudio, el primero de estas características, se ha llevado a cabo un análisis exergético teniendo en cuenta la información disponible de las 40 minas más importantes a nivel mundial de los minerales metálicos más importantes económicamente.

    a. La principal contribución es la validación y mejora de la Geonomía Física comparando los datos teóricos del uso energético en la industrial mineral con datos empíricos. Esta comparación se ha podido llevar a cabo para el caso del cobre, oro y zinc. Partiendo de este análisis, se han podido calcular nuevos y más precisos valores de los costes exergéticos de reposición de dichas sustancias.

    b. Adicionalmente, en el Capítulo 2 se ha llevado a cabo un análisis del uso de la energía en la industria minera a lo largo del tiempo, teniendo en cuenta el consumo de electricidad y de combustible diesel en función de la ley del mineral. Al mismo tiempo se ha analizado la influencia del tipo de proceso existente en la mina (concentrado, refinado, lixiviado) y del tipo de mina (cielo abierto, interior).

    c. Partiendo de la información obtenida para las distintas minas de cobre, se han analizado los cambios globales del contenido en cobre en las minas a lo largo del tiempo, así como su relación con el consumo energético.

   d. La última contribución de este capítulo ha sido la estimación de los costes exergéticos de reposición para el galio, germanio e indio, sustancias que son extremadamente críticas para el desarrollo de las energías renovables y cuyos costes de reposición no habían sido calculados antes.

   e. Con los resultados obtenidos se está elaborando un artículo científico cuyo título provisional es: *Energy intensity factors in gold, copper, lead and zinc mining projects.*

2. Dado que el agotamiento de los recursos minerales es un problema global, es necesario desarrollar indicadores que puedan evaluar de forma adecuada esta problemática. Por tanto, la principal contribución del **Capítulo 3** es la propuesta de un indicador global a la Comisión Europea para evaluar el uso eficiente de los recursos empleando un enfoque basado en la termodinámica: GDP/DMD.

   a. Este indicador propuesto (GDP/DMD) puede ser empleado para valorar adecuadamente la dispersión mineral, incorporando los costes exergéticos de reposición (ERC) en los cálculos. Esto se ha corroborado con un caso práctico basado en los datos de comercio mineral en España.

   b. Con los resultados obtenidos se publicó el siguiente artículo científico (**Artículo I**): *Using thermodynamics to improve the resource efficiency indicator GDP/DMC.*

3. La principal contribución del **Capítulo 4** ha sido convertir los costes exergéticos de reposición a costes monetarios, obteniendo así valores teóricos de los precios que deberían tener los minerales en el mercado si tuvieran en cuenta estos costes de reposición.

   c. Una vez se han incorporado los costes exergéticos de reposición en los precios de mercado de los minerales, se ha podido observar que los nuevos valores son de 10 a 80 veces mayores que los iniciales, siendo la media 27 veces mayor. Este enfoque permite ver la diferencia entre una situación en la que los recursos son tratados como bienes ordinarios y otra en la que son tratados como activos físicos que deben ser reemplazados.

   d. Con los resultados obtenidos se elaboró el siguiente artículo científico (**Artículo II**): *How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study*.

4. En el **Capítulo 5** la Geonomía Física ha sido aplicada por primera vez a escala macroscópica a través de tres casos de estudio para evaluar la

dispersión mineral: España, Europa (EU-28) y Colombia. Este análisis se ha llevado a cabo mediante el uso de diagramas Sankey, expresados tanto en toneladas como en costes exergéticos de reposición, para poder observar el flujo de recursos minerales, combustibles fósiles y minerales, dentro de una misma región.

a. La primera contribución ha sido el análisis detallado de la extracción mineral en España durante el siglo XX, tanto en el caso de minerales como de combustibles fósiles. Partiendo de esta información se ha podido valorar el grado de agotamiento de los recursos minerales españoles teniendo en cuenta las estimaciones de reservas. Del mismo modo se ha podido analizar el impacto de las importaciones, exportaciones y consumo. Esta información se publicó en el siguiente artículo científico (**Artículo III**): *An exergoecological analysis of the mineral economy in Spain.*

b. La segunda contribución ha sido la realización de un análisis de flujo de materiales en Europa (EU-28) desde 1995 hasta 2012 empleando para ello la exergía y más concretamente los costes exergéticos de reposición. Para ello se ha tenido en cuenta la extracción interna de cada país, las importaciones, exportaciones, consumo y reciclado. Con estos datos se ha podido analizar el déficit comercial y la dependencia del exterior en cuanto al uso de minerales. Con estos resultados se ha publicado un artículo en una revista científica (**Artículo IV**): *Material flow analysisfor Europe: an exergoecological approach.*

c. La última contribución ha consistido en analizar los costes monetarios asociados con la extracción mineral en el caso de España y Colombia, y comparar estos resultados con las ganancias generadas por el sector minero y el producto interior bruto (PIB). Estos resultados están plasmados en el artículo *Physical assessment of the mineral capital of a nation: the case of an importing and an exporting country*, pendiente de publicación.

PUBLICACIONES CIENTÍFICAS

El trabajo de investigación principal que ha sido llevado a cabo en esta tesis doctoral ha resultado en 4 artículos científicos publicados en revistas de alto impacto incluidas en el Journal Citation Reports (JCR). La información restante ha dado lugar a dos artículos más, uno de los cuales está siendo revisado por una revista mientras que el otro artículo está todavía en preparación. Todas estas contribuciones están enumeradas en la Tabla 26.

Se han presentado un total de 7 contribuciones a congresos de ámbito nacional e internacional y una de ellas, *An exergoecological analysis of the* *mineral economy in Spain*, presentada en el congreso ECOS 2014, recibió el premio al Mejor Artículo. Todas estas contribuciones se pueden ver en la Tabla 27.

Adicionalmente, se ha publicado un artículo de divulgación en el Boletín Informativo del Colegio Oficial de Ingenieros Técnicos de Minas y Grado en Minas y Energía de Aragón.

Autora: Calvo, Guiomar
Título del artículo: Agotamiento de los recursos minerales de España
Publicación: Boletín Informativo Colegio Oficial de Ingenieros Técnicos de Minas y de Grado en Minas y Energía de Aragón. Número 24.
Fecha: Junio 2014.

Finalmente, como resultado del trabajo presentado en esta tesis, también se ha publicado un capítulo en un libro.

Autores: Valero, Alicia; Valero, Antonio; Calvo, Guiomar.
Título: Agotamiento del capital mineral de la Tierra
Libro: Los inciertos pasos desde aquí hasta allá: Alternativas socio ecológicas y transiciones postcapitalistas
Fecha: 2015.
Editorial: Editorial Universidad de Granada.
Editores: Riechmann, J., Carpintero, Ó and Matarán, A.
ISBN: 978-84-338-5715-6.

Tabla 26. Artículos científicos derivados de esta tesis.

Núm.	Título	Autores	Título de la revista	DOI	Factor de impacto	Estado
1	How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study.	Valero, Antonio; Carpintero, Óscar; Valero, Alicia and **Calvo, Guiomar**.	*Ecological Indicators*	http://dx.doi.org/10.1016/j.ecolind.2014.07.021	3.444	Publicado (2014)
2	Using thermodynamics to improve the resource efficiency indicator GDP/DMC.	Valero, Alicia; Valero, Antonio and **Calvo, Guiomar**.	*Resources, Conservation and Recycling*	http://dx.doi.org/10.1016/j.resconrec.2014.12.001	2.564	Publicado (2015)
3	An exergoecological analysis of the mineral economy in Spain.	**Calvo, Guiomar**; Valero, Alicia; Valero, Antonio and Carpintero, Óscar.	*Energy*	http://dx.doi.org/10.1016/j.energy.2015.01.083	4.844	Publicado (2015)
4	Material flow analysis for Europe. An exergoecological approach.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	*Ecological Indicators*	http://dx.doi.org/10.1016/j.ecolind.2015.08.005	3.444	Publicado (2016)
5	Physical assessment of the mineral capital of a nation: the case of an importing and an exporting country.	**Calvo, Guiomar;** Valero, Alicia; Carmona, Luis Gabriel and Whiting, Kai	*Resources ISSN 2079-9276*	-	-	*Envíado a revista (09/2015)*
6	Energy intensity factors in gold, copper, lead and zinc mining projects.	**Calvo, Guiomar;** Valero, Alicia; Mudd, Gavin	-	-	-	*En pre-paración*

Tabla 27. Contribuciones en congresos nacionales e internacionales.
(*) Premio al Mejor Artículo.

Núm	Título	Autores	Congreso	Fecha y lugar
1	Detalles históricos sobre la producción de wolframio y estaño en España.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	XIII Congreso Internacional sobre Patrimonio Geológico y Minero.	Manresa, España. Septiembre 2012.
2	Is the lead indicator GDP/DMC preliminarily proposed by the European Commission an appropriate indicator to measure resource efficiency?	Valero, Antonio; Valero, Alicia and **Calvo, Guiomar**.	Fourth Aachen International mining Symposia (AIMS).	Aachen, Alemania. Mayo 2013.
3	How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study.	Valero, Antonio; Valero, Alicia; **Calvo, Guiomar** and Carpintero, Óscar.	10th biennal conference of the European Society for Ecological Economics (ESEE).	Lille, Francia. Junio 2013.
4	An exergoecological analysis of the mineral economy in Spain. (*)	Valero, Antonio; Valero, Alicia; **Calvo, Guiomar** and Carpintero, Óscar.	27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental impact of Energy Systems (ECOS).	Turku, Finlandia. Junio, 2014.
5	Sankey and Grassmann diagrams for mineral trade in the EU-28.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	7th International Exergy, Energy and Environment Symposium (IEEES).	Valenciennes, Francia. Abril, 2015.
6	Exergy as a resource efficiency indicator for industries.	Valero, Alicia; Valdés, Marianela and **Calvo, Guiomar**.	28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS).	Pau, Francia. Junio-Julio, 2015.
7	Material flow analysis for Europe. A thermodynamic approach.	**Calvo, Guiomar**; Valero, Alicia and Valero, Antonio.	8th Conference of the International Society for Industrial Ecology (ISIE).	Guildford, Reino Unido. Julio, 2015.

PERSPECTIVAS

Teniendo en cuenta los resultados y las conclusiones obtenidas a partir del trabajo desarrollado durante la elaboración de esta tesis doctoral, se han identificado distintas líneas de investigación que se podrán desarrollar como continuación del trabajo aquí presentado.

En esta tesis doctoral se han obtenido los costes exergéticos de reposición de 6 minerales, pero solo la mitad de estos valores están basados en datos de consumo real de energía en función de la ley del mineral. Es imprescindible contar con datos empíricos para otras sustancias para seguir mejorando la metodología y tener unos valores de costes exergéticos de reposición de cada mineral lo más precisos y fiables posible. Por tanto, se debe ampliar el estudio y tratar de conseguir información real de consumo energético en el caso de otros minerales.

De la misma forma, el análisis energético llevado a cabo para estudiar la relación entre el consumo energético y la ley del mineral para verificar su posible relación solo cuenta con información procedente de 40 minas, por lo que se debería añadir información procedente de otras explotaciones para tener una imagen más precisa de dicha relación.

Hasta ahora, el análisis de flujo de materiales se ha llevado a cabo a escala macroscópica, empleando el flujo de recursos minerales en distintos países y territorios como caso de estudio. Este mismo análisis podría ser llevado a menor escala, analizando aparatos electrónicos y, en general, las nuevas tecnologías como pueden ser las renovables y estudiar los flujos de materiales que son necesarios para producirlas.

Otro estudio complementario consistía en incluir la Geonomía Física en la metodología tradicional del Análisis de Ciclo de Vida (ACV). Normalmente el ACV emplea una metodología llamada “de la cuna a la tumba” e introduciendo los costes exergéticos de reposición en dicha metodología se puede añadir el enfoque “de la tumba a la cuna”, cerrando así el ciclo y obteniendo un enfoque global.

Para pasar del nivel teórico al práctico, y para mejorar la gestión de recursos minerales, es de vital importancia que las naciones dispongan de un sistema de contabilidad que sea capaz de tener en cuenta y evaluar la pérdida de capital mineral. Un buen punto de partida es el Sistema de Contabilidad Económico Ambiental (SEEA) propuesto por Naciones Unidas. Sin embargo, el SEEA debería ir más allá y transformarse en un Sistema Global de Contabilidad Económico Ambiental (SETEA), donde la unidad de medida de los recursos sean los costes exergéticos de reposición en vez de las toneladas, pudiendo evaluar así la dispersión del capital mineral. Por este motivo, partiendo del SEEA, se podría desarrollar una nueva, más fuerte y más práctica estructura para mejorar la gestión de recursos limitados y críticos.