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Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints

Annex 6: Task 2.2.d.2. Exergy replacement costs for the materials used in the European economy

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Task: Annex 6: Task 2.2.d.2. Exergy replacement costs for the materials used in the European economy

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Scope of document

This report is part of subtask 2.2.d.2 within Task WP2.2.The main goal of this subtask was to generate a document able to evaluate the Exergy Replacement Costs (ERC) associated to the material consumption in the industrial, residential and commercial sectors in the European economy. To that end, after a thorough analysis of state of the art available information, we came to the conclusion that such data is nowadays not available. To our knowledge, the most advanced data base should be generated by the Joint Research Centre (JRC), through the Raw Materials Information System (RMIS). The JRC is currently gathering information to provide a structured repository of knowledge on non-energy and non-agricultural raw materials from primary and secondary sources. Today, only information for three elements is available: Al, Co and P and this information is only qualitative (see Figure below).

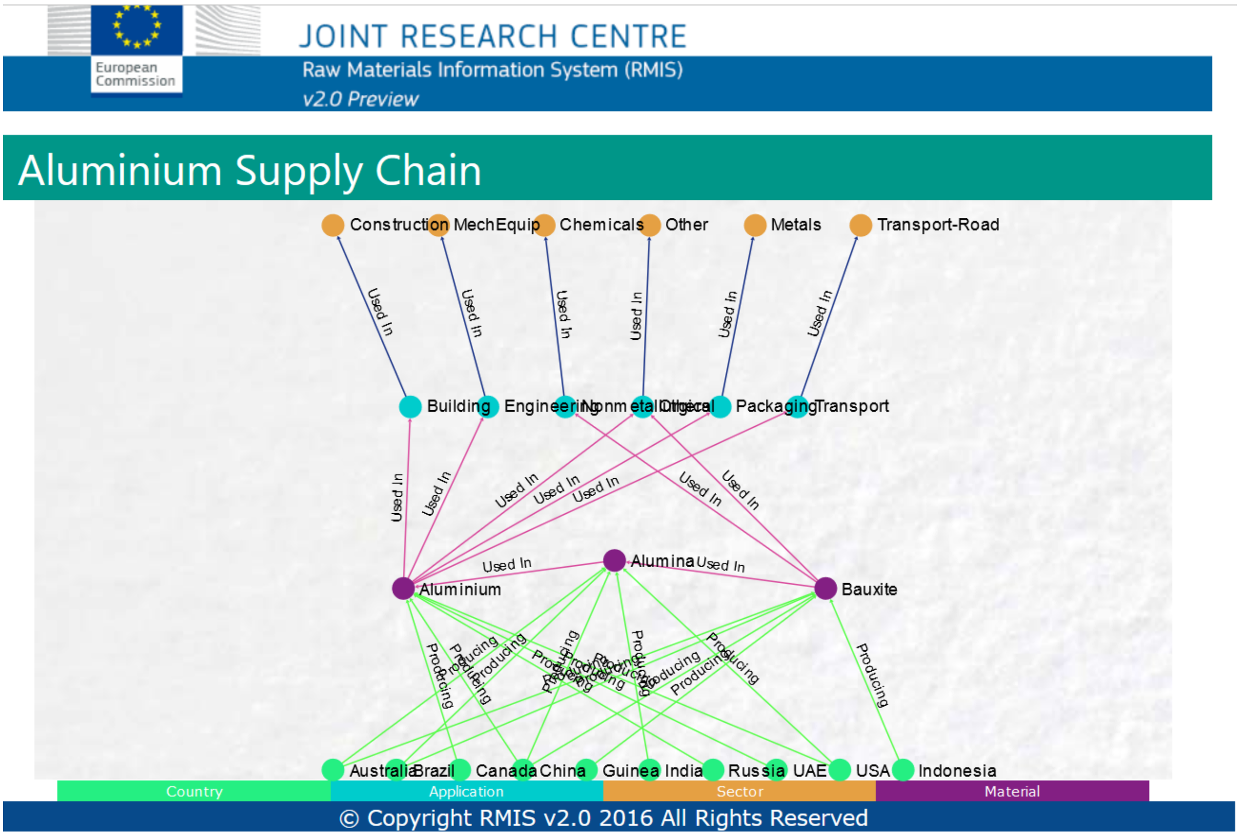

Figure 1. *Aluminium supply chain according to the RMIS database: http://rmis.jrc.ec.europa.eu/v2/fiches/*

Additionally, the report on Critical Raw Materials for the European Economy (European Commission 2014a, 2014b) provides some data on mineral used in different sectors but in a very aggregated form. Still, even if there are some initiatives that are currently trying to compile information regarding material use per sector, there is not enough information to perform a complete analysis. That is the reason why instead of carrying out the analysis by sectors, a macro analysis for Europe has been performed. Important also to MEDEAS model is to make sure that critical raw materials are incorporated. This is why this report analyses the different criticality assessments existing in the literature and how the exergy approach (proposed to be used in MEDEAS) relates to them. In summary, the following information is included in this report:

1. Literature review on criticality assessment of raw materials
2. Comparison of the exergy replacement cost analysis with other criticality assessments
3. Critical material flow analysis for Europe through the exergy approach

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Introduction

Concern on the availability of raw materials has led to an increment in reports that assess the criticality of minerals. These classifications and lists vary between each country due to different approaches and targets, but also according to domestic availability and demand and to predictable changes in technology and policies. Multiple studies have compared the different approaches between the traditional methodologies used to assess the criticality of non-fuel minerals, focusing on the advantages and drawbacks of each one of them (Erdmann and Graedel, 2011; Glöser et al., 2015; Graedel and Reck, 2015; Helbig et al., 2016; Jin et al., 2016; Skirrow et al., 2013; UKERC, 2014; Zepf et al., 2014).

At world level, many countries have developed criticality assessment reports. The United States has a long tradition related with analyzing the materials that are critical, concerning security interests. The National Defense Stockpile (NDS Program) monitors 160 minerals, of which 92 meet at least one of the vulnerability metrics measured (U.S. Department of Defense, 2015). Additionally, reports concerning the critical material strategy of the U.S. have been developed as well taking into account the internal demand (U.S. Department of Energy, 2011). Other countries, such as Japan and Korea, that have been historically dependent on imports of various non-fuel and fossil fuels minerals from overseas, have also developed strategies concerning raw materials (Bae, 2000; Hatayama and Tahara, 2015; JOGMEC, 2010; Kawamoto, 2008). Regarding territories that are major global mineral exporters, such as Australia, the criticality assessments rely more on their own resource potential to cover the global demand than on assessing external sources (Skirrow et al., 2013).

In the European Union the initial concern on raw material supply started decades ago (European Commission, 1975), and this issue has been progressively becoming more and more relevant, establishing policies to reduce the use and dependency and elaborating several reports on this matter (European Commission, 2014a, 2010). The methodology used to assess the criticality of the fifty-four raw materials analyzed by the European Commission takes into account several factors. The first one being economic importance, calculated assessing the production of each material associated with megasectors at EU level and combining it with the megasector's gross value added to the EU's GDP. The second factor is the supply risk, divided into two categories: the supply risk linked to poor governance, and the environmental country risk linked to low environmental standards. In both cases, the supply risk is a combination of substitutability, end-of-life recycling rates and high concentration of producing countries with either poor governance or low environmental standards. In the case of supply risk, it only applies to primary production and

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could be reduced if more recycling is undertaken or if a raw material could be substituted. In the first report, elaborated in 2010, fourteen of those fifty-four raw materials were classified as critical. In the updated report, made public during 2014, the list of critical raw materials increased to twenty elements, including thirteen elements previously identified as critical. Tantalum was removed from the list, as the supply risk decreased, and borates, chromium, coking coal, magnesite, phosphate rock and silicon metal were included. Additionally, the British Geological Survey (BGS) publishes yearly an updated risk list to provide a simple indication on the relative risk of a certain number of commodities that are needed to maintain the economy and lifestyle (British Geological Survey, 2015).

Meanwhile, other studies have focused not on specific countries but on the critical raw materials that are necessary to develop emerging or green technologies or in the strategies of securing a stable supply of certain minerals (Angerer et al., 2009; APS Physics, 2011; Barteková and Kemp, 2016; Resnick Institute, 2011). For instance, the Joint Research Centre (JRC) along with the Institute for Energy and Transport (EIT) analyzed the possible bottlenecks of metals in strategic energy technologies (Moss et al., 2011). Besides, several articles have analyzed the criticality of selected elements. Harper et al. (2015) analyzed zinc, tin and lead family minerals. Nassar et al. (2015) analyzed rare earth elements and Panousi et al. (2015) focused on seven specialty metals: scandium, strontium, antimony, barium, mercury, thallium and bismuth. In all the cases, the factors analyzed were supply risk, environmental applications and vulnerability to supply.

When observing the critical raw materials selected in each report it can be seen that not all of them label as critical the same substances. There does not seem to be any global criteria that can help to evaluate the criticality of mineral commodities nor an approach that provides an assessment independent of market and political arbitrariness and that is rooted in the geological and physico-chemical characteristics of minerals. Therefore, a thermodynamic approach that is going to be used in this report to fill that void. A first approach to evaluate the material flow analysis in Spain and in Europe was previously carried out taking into account fossil fuels and main mineral commodities (Calvo et al., 2016, 2015). At European level, the average weight in mass terms of critical minerals was less than 1% when compared with the total domestic extraction in the EU-28 for 2011. Yet such seemingly small amount might become crucial for future economic development. This is why this study tries to get a more precise picture of the substances labeled as critical, providing a new approach that complements the existing information with a thermodynamic perspective, using exergy analysis. This way, not only the quantity, but also the quality of mineral resources is considered in the assessment. The main goal is to verify if the so-called critical raw materials are not only critical from an economic perspective, but also from a

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thermodynamic one. The analysis is then applied to perform an EU-28 material flow analysis for 2014 so as to identify the most critical substances for the region not only in physical terms but in thermodynamic terms.

Thermodynamic rarity

The whole extraction rate of mineral resources needs to be quantitative and qualitatively studied. Common units of measure are mass and monetary prices and tonnage can directly be obtained from statistical services and mining companies. However such an accounting adds commodities extracted massively with others having an insignificant contribution, i.e. aluminum and gallium. Hence "minor" substances become eclipsed thus neglecting their importance. The alternative is to use the monetary approach. However, price volatility driven by market and political factors distorts the physical reality of the loss of resources. Valero (1998) proposed instead a thermodynamic approach. The Exergoecology method uses exergy as a yardstick since it does not depend on market and reflects both the quantity and quality of extracted minerals. Exergy measures the degree of thermodynamic distinction a material piece has from its surrounding commonness. Therefore it allows to physically measure the "rarity" of a piece of matter since the rarer it is, the more it stands out (Valero and Valero, 2014).

Thermodynamic rarity was defined (Valero and Valero, 2015, 2014) as the amount of exergy needed to obtain a given commodity from an ordinary rock with prevailing technologies. In fact, exergy accurately measures, in energy terms, the distinction of a piece of matter with respect to a given reference environment (R.E.), sometimes also known as the "dead state". When dealing with mineral resources, this dead state is called Thanatia.

Thanatia represents a resource-exhausted Earth composed of the 292 most common ordinary rocks. This ideal model becomes practical when one knows that: first, all minerals and fossil fuel deposits that ever existed constitute less than 0.01-0.001% of the earth crust. Second, the complete combustion of all earths fossil fuels will "only" change the composition of current atmosphere, in parts per million of CO2 increase, only six or eight times more than at present. Third, approximately 3% of hydrosphere appears as freshwater in glaciers and icecaps, groundwater, lakes, soil, the atmosphere and biosphere. Only 0.33% of the total amount of freshwater is concentrated in lakes, reservoirs and river systems. Such subtle part though is in the utmost danger of being polluted. Considering these numbers, abiotic resources are deeply scarce in the planet. Thereby Thanatia hypothesis implicitly considers that all mineral deposits have been ultimately extracted and all chemical elements oxidized and dispersed throughout the crust. In

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such a way, Thanatia may be used as a starting point to assess the mineral capital depletion of the planet. Each and every irreversible dispersion of any mineral represents a tiny step to Thanatia (Alicia Valero et al., 2011; Antonio Valero et al., 2011).

Rarity incorporates two types of costs. First, a real one, accounting for the exergy resources needed to convert a mineral into a commodity –i.e. beneficiation, smelting and refining processes. In other words, it is the embodied exergy (or exergy cost, kWh) of the mineral from mine to market. Second, a hidden cost, understood as the free natural bonus provided by Nature for having minerals concentrated in mines instead of dispersed throughout the crust (from Thanatia to the mine). This free natural bonus is represented by the exergy replacement cost (ERC), defined as the exergy that would be needed to extract a mineral from ordinary rocks (Thanatia state) to the conditions of concentration and composition found in the mine, using prevailing technology. Note that both costs are defined as embodied exergies rather than embodied energies. This is because minerals commonly appear with valuable companion metals/substances whose energy consumptions need precise allocations. Regrettably, in the absence of accurate analyses, the embodied energies may be used as “surrogate numbers” of their exergy costs. This is even worse news when they are at the beginning of the value chain of commodities, as it distorts all subsequent calculations.

Rarity varies from mineral to mineral, as is a function of a mineral’s absolute scarcity in Nature and the state of technology. A mineral is here denoted as “scarce”, when its exergy replacement cost is high. This happens when the ore grade in Thanatia (x_c) is low, the difference between the ore grade in the mine (x_m) and in Thanatia is high and when the energy required to beneficiate the given mineral is important. Presently known thermodynamic rarity values are listed in Table 1 as well as values of ERC, mining, concentration, smelting and refining values in GJ/t. The information summarized in the table is an update of an extensive literature review carried out in Valero and Valero (2014) for the geology, mining and metallurgy of different mineral commodities.

It should be noted that thermodynamic rarity values are not static. They can slowly change over time as extractive technologies increase their efficiency or because better data about global extraction and global ore grades are available. Still, they can be used as a reference to provide simple and straightforward information to identify which minerals are more critical from a thermodynamic perspective.

As stated before, a very relevant factor is the average concentration in the crust (x_c), in the mine (x_m) and the energy needed to extract and process each element. The concentration or ore grade of a mineral in the mine can be determinant for the energy consumption in the mining, smelting and refining processes. As several studies have shown, when the ore grade decreases in a mine the energy needed to extract the mineral increases (Mudd, 2010, 2007; Norgate et al., 2007; Talens and Villalba, 2013).

In the case of antimony, for instance, a mineral that has a medium value of thermodynamic rarity, there is a big difference between the concentration in the mines and in the crust, which is reflected by a high value of ERC (474 GJ/t), and lower values of mining, concentration, smelting and refining energy when compared to other minerals (1.4 GJ/t and 12.0 GJ/t respectively). In the case of tellurium, a mineral with a high thermodynamic rarity value, both the average ore grade in the crust and in the mine are very low when compared to other minerals, and the energy needed to extract and concentrate this element is indeed very high (589,366 GJ/t). Combining these two factors, the final value of thermodynamic rarity is both dependent not only on the ore grade, but also on the technology and processes used to extract the element.

In this study, we have considered the following limits to create three risk categories of high, medium or low values of thermodynamic rarity, all measured in GJ/t. High value correspond to values greater than 10,000 GJ/t (such as cobalt, gallium or gold), medium values are between 100 and 10,000 GJ/t (such as aluminum, bismuth or nickel) and low are less than 100 GJ/t, such as chromium or graphite. This approach provides more objective and accurate information on how severe is the loss, or better say, dispersion, of each respective material at the end of life.

Table 1. Values of ERC, thermodynamic rarity and energy needed for the mining, concentration, smelting and refining stages for selected commodities (updated from Valero and Valero, 2014).

Mineral	x_c [g/g]	x_m [g/g]	ERC [GJ/t]	Mining and conc. [GJ/t]	Smelting and refining [GJ/t]	Thermodynamic rarity [GJ/t]
Aluminium (Gibbsite)	1.38E-03	7.03E-01	627	10.5	23.9	661.4
Antimony (Stibnite)	2.75E-07	5.27E-02	474	1.4	12.0	487.4
Arsenic (Arsenopyrite)	4.71E-06	2.17E-02	400	9.0	19.0	427.0
Barite	7.09E-04	9.50E-01	38	0.9	-	38.9
Beryllium (Beryl)	3.22E-05	7.80E-02	253	7.2	450.0	710.2
Bismuth (Bismuthinite)	5.10E-08	2.46E-03	489	3.6	52.8	545.4
Cadmium (Greenockite)	1.16E-07	1.28E-04	5,898	263.9	278.5	6,440.4
Chromium (Chromite)	1.03E-04	3.00E-04	4.5	0.1	36.3	40.9

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Cobalt (Linnaeite)	1.98E-04	6.37E-01	10,872	9.2	129.0	11,010.2
Copper (Chalcopyrite)	5.15E-09	1.90E-03	292	35.3	21.4	348.7
Fluorite	6.64E-05	1.67E-02	183	1.5	-	184.5
Gallium (in Bauxite)	1.12E-05	2.50E-01	144,828	610,000.0	-	754,828.0
Germanium (in Zinc)	1.30E-04	3.00E-04	23,750	498.0	-	24,248.0
Gold	1.76E-05	5.00E-05	553,044	110016.1	-	663,060.1
Graphite	1.41E-06	3.00E-03	20.39	1.1		21.5
Gypsum	1.28E-09	2.24E-06	15	0.2	-	15.2
Indium (in Zinc)	5.61E-08	4.50E-04	360,598	3319.7	-	363,917.7
Iron ore (Hematite)	9.66E-04	7.30E-01	18	0.7	13.4	32.1
Lead (Galena)	6.67E-06	2.37E-02	37	0.9	3.3	41.2
Lime	8.00E-03	6.00E-01	2.6	0.4	5.8	8.8
Lithium (Spodumene)	3.83E-04	8.04E-01	546	12.5	420.0	978.5
Magnesite	2.50E-02	4.20E-01	26	9.5		35.5
Manganese (Pyrolusite)	4.90E-05	5.00E-01	16	0.2	57.4	73.6
Mercury (Cinnabar)	5.73E-08	4.41E-03	28,298	157.0	252.0	28,707.0
Molybdenum (Molybdenite)	1.83E-06	5.01E-04	908	136.0	12.0	1,056.0
Nickel (sulphides) Pentlandite	5.75E-05	3.36E-02	761	15.5	100.0	876.5
Nickel (laterites) Garnierite	4.10E-06	4.42E-02	168	1.7	412.0	581.7
Niobium (ferrocolumbite)	8.10E-06	2.00E-02	4,422	132.0	-	4554.0
Palladium	3.95E-10	8.02E-07	8,983,377	583333.3	-	9,566,710.3
Phosphate rock (Apatite)	4.03E-04	5.97E-03	0.4	0.3	4.6	5.3
Platinum	3.95E-10	8.02E-07	4,491,69	291666.7	-	4,783,356.7
Potassium (Sylvite)	2.05E-06	3.99E-01	665	1.7	-	666.7
REE (Bastnaesite)	2.54E-07	6.00E-02	348	10.2	3.7	361.9
Rhenium	1.98E-10	2.33E-04	102,931	156.0	-	103,087.0
Silver (Argentite)	1.24E-08	4.27E-06	7,371	1281.4	284.8	8,937.6
Sodium (Halite)	5.89E-04	2.00E-01	44.07	3.3	39.6	86.9
Tantalum (Tantalite)	1.58E-07	7.44E-03	482,828	3082.8	8.1	485,918.9
Tellurium (Tetradymite)	5.00E-09	1.00E-06	2,235,699	589366.1	39.2	2,825,104.3
Tin (Cassiterite)	2.61E-06	6.09E-03	426	15.2	11.4	452.6

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Titanium (Ilmenite)	4.71E-03	2.42E-02	4.5	7.2	128.1	139.8
Titanium (Rutile)	2.73E-04	2.10E-03	8.8	13.8	243.8	266.4
Tungsten (Scheelite)	2.67E-06	8.94E-03	7,430	213.0	381.0	8,024.0
Uranium (Uraninite)	1.51E-06	3.18E-03	901	188.8	-	1,089.8
Vanadium	9.70E-05	2.00E-02	1,055	136.0	381.0	1,572.0
Yttrium-Monazite	1.30E-04	3.00E-04	159	1198.3	-	1,357.3
Zinc (Sphalerite)	9.96E-05	6.05E-02	155	1.5	40.4	196.9
Zirconium (Zircon)	3.88E-04	4.02E-03	654.43	738.5	633.0	2,025.5

New list of critical raw materials

Taking into account this information, a comparison between the different approaches used in these reports and a thermodynamic approach can be carried out. Table 2 represents a summary of the different reports analyzed and incorporates information on the thermodynamic rarity of each commodity as well.

***Table 1**. Comparison of critical material lists from different studies.*

▯ = high risk, ◐ = medium risk, ○ = low risk. When there is no categorization available, the risk has been considered high. In the case of BGS (2015) risk list, only the minerals with a risk 6 or higher have been included. As for thermodynamic rarity values it represents high, medium or low values (in GJ/t).

Element	EC (2014)	Bae (2000)	Angerer et al. (2009)	JOGMEC (2010)	EC (2010)	APS Physics (2011)	Resnick institute (2011)	DOE (2011)	Moss et al. (2011)	UKERK (2014)	BGS (2015)	Thermo-dynamic rarity (Valero and Valero, 2014)
Aluminium		○									○	◐
Antimony	▯	◐	▯	○	▯						▯	◐
Arsenic											◐	◐
Barium											◐	○
Beryllium	▯				▯						◐	◐
Bismuth											▯	◐
Borates	▯											–
Cadmium							▯		○		◐	◐
Chromium	▯	◐		▯					◐		◐	○
Cobalt	▯	◐	▯	▯	▯	▯	▯	○	◐	▯	▯	▯
Coking coal	▯											–
Copper		○	▯						○		○	◐
Fluorspar	▯				▯						◐	◐
Gallium	▯	▯	▯	▯	▯	▯	▯	○	▯	▯	▯	▯
Germanium	▯		▯		▯	▯	▯		▯	▯	▯	▯
Gold									○		○	▯
Graphite	▯				▯				▯		◐	○
Hafnium									▯			–

Indium	▯	▯	▯	▯	▯	▯	▯	◐	▯	▯	▯	▯
Iron											○	○
Lead		○							○		○	○
Lithium		▯		○		▯	▯	◐	○	▯	◐	◐
Magnesite	▯	▯			▯			○			◐	○
Manganese		◐		▯				○				○
Mercury											◐	▯
Molybdenum		◐		▯					○		▯	◐
Nickel		▯		▯				○	○		○	◐
Niobium		◐	▯	◐	▯		▯		◐		◐	◐
PGM	▯	▯	▯	◐	▯	▯	▯		▯	▯	◐	▯
Phosphate rock	▯											○
REE	▯	▯	▯	◐	▯	▯	▯	▯	▯	▯	▯	◐
Selenium		◐	▯			▯	▯		○	▯	◐	▯
Silicon (metal)	▯	▯										○
Silver			▯			▯	▯		○	▯	◐	◐
Strontium				◐							▯	–
Tantalum			▯	◐	▯				◐		◐	▯
Tellurium						▯	▯	◐	▯	▯		▯
Thallium		◐										–
Thorium											○	–
Tin			▯						◐		○	◐
Titanium		▯	▯	○							○	◐
Tungsten	▯	▯		▯	▯						▯	◐
Uranium											○	◐
Vanadium		◐		▯				○	◐		▯	◐

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Zinc		○									○	◐
Zirconium		▯									◐	◐

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As this report focuses on the mineral scarcity and trade in the EU-28, the list of critical raw materials selected by the European Commission (European Commission 2014a) is used as a reference for this comparative analysis.

Starting with the values provided for the supply risk for different mineral commodities, we can see in Figure 1 the thermodynamic rarity values of the commodities as a function of the supply risk (due to data variations, the vertical axis is in logarithmic scale). The commodities represented in grey are those considered critical by the European Commission in the 2014 report.

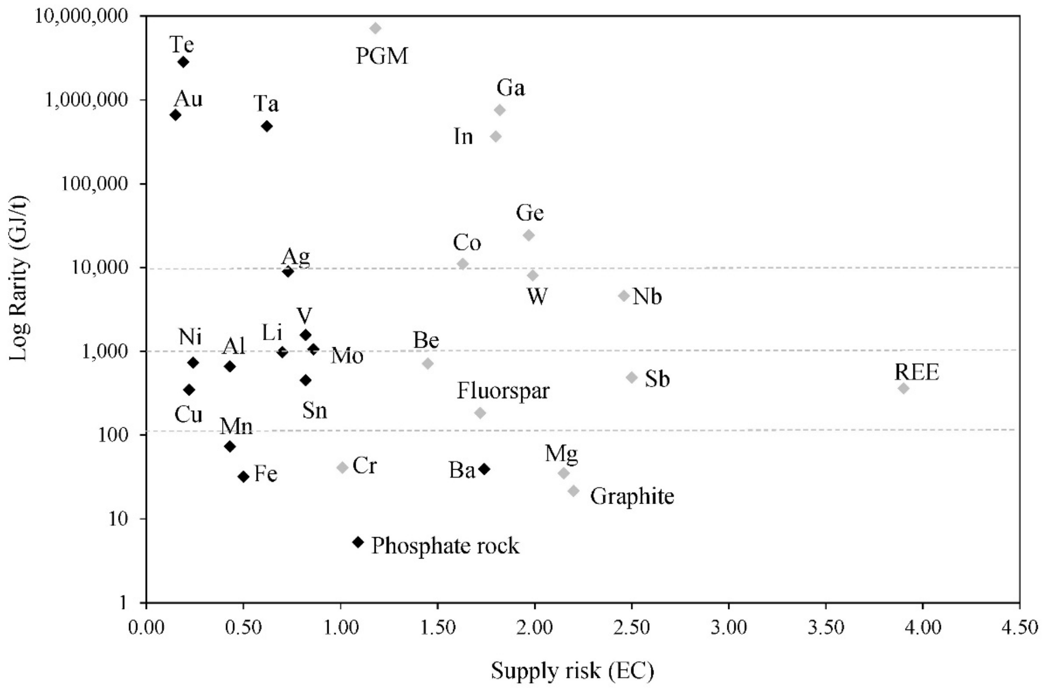

Figure 2. *Thermodynamic Rarity as a function of the supply risk (data according to the European Commission, 2014b). Elements in grey are those labeled as critical by the European Commission.*

When comparing these two variables, it is obvious that there are some commodities which have high values of thermodynamic rarity, meaning that are more scarce and difficult to extract, such as gold, tantalum or tellurium. Even so, they are not considered critical from a supply risk point of view by the European Commission. Tantalum was indeed included in the European Commission report of 2010, but was excluded in 2014 as it was stated that the supply risk had decreased. Even if the extraction data coming from conflict regions are not always accurate, Congo production in 2000 was 9% of the total share and 17% in 2014. In the case of Rwanda, it was the leading tantalum producer in 2015, with a share of 50% of the total world production, and has displaced

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Australia and Congo as the main producers. Tantalum has been and is a conflict mineral, therefore we propose to label it as critical.

Additionally there are other minerals that have high thermodynamic rarity values but are not included in the critical raw material list of the European Commission, such is the case of silver, vanadium, nickel, molybdenum or lithium. On the contrary, other commodities with lower values of thermodynamic rarity are indeed considered as critical, such as magnesite, graphite or chromium.

These results can be combined with those presented in Figure 2, showing thermodynamic rarity values as a function of the economic importance. Again, the values in grey represent those commodities selected as critical by the European Commission in the 2014 report and similar results can be inferred. Substances, such as tantalum, gold, lithium and vanadium that are critical when considering thermodynamic rarity values, are not considered critical when assessing only economic importance.

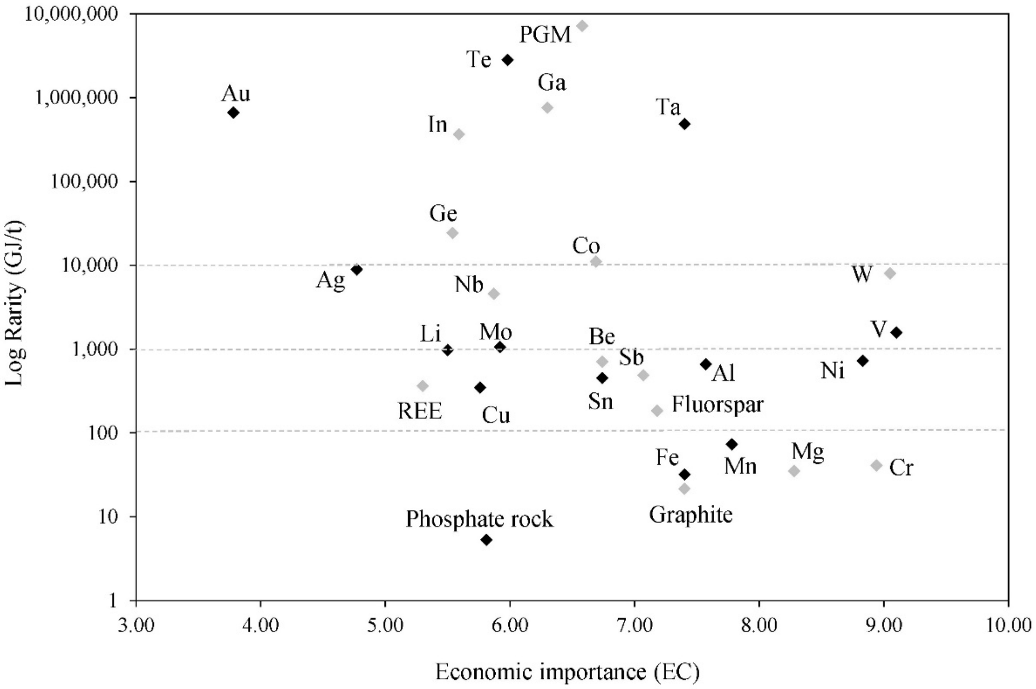

Figure 3. *Thermodynamic rarity as a function of the economic importance (data according to the European Commission, 2014b). Elements in grey are those labeled as critical by the European Commission.*

Therefore, the new critical mineral list, taking into account not only scarcity or economic factors, but also using a thermodynamic perspective, contains the following minerals: antimony, chromium, cobalt, gallium, germanium, indium, lithium, magnesite, molybdenum, nickel, niobium, PGM, phosphate rock, REE, silver, tantalum, tellurium, tungsten and vanadium.

Clearly, substances such as gallium, germanium and indium are present, and are considered critical in the vast majority of the analyzed reports, but others such as lithium, molybdenum or vanadium are also included in this study as they are critical from a thermodynamic perspective. Taking into account market and political factors, cadmium and hafnium are listed as metals that are not expected to generate bottlenecks in the next decade as the growth in demand is expected to be very low. Besides, selenium and tin are metals that are listed as medium risk, as even if there are no significant political risks, the demand is expected to increase rapidly in the case of selenium (Moss et al. 2011). Other substances usually considered critical are borates, mainly used for agriculture, ceramics and glass, or coking coal. Yet from an Exergoecology perspective, the values of thermodynamic rarity of borates, hafnium and selenium have not yet been estimated and cannot be included in the analysis, but for the remaining metals, only cadmium presents a high thermodynamic rarity value (6,440.8 GJ/t). Still, considering the health and environmental concerns associated with this element and the increasingly restrictive regulations it is not going to be included in the material flow analysis. On the other hand, there are materials that are usually not labeled as critical in the assessment reports, such is the case of phosphate rock, but as it is needed in huge quantities for fertilizers, it is also going to be included in this analysis. Additionally, even if nickel is not considered as very critical in the reports, as it has a medium value of thermodynamic rarity and that the EU-28 only is able to provide around 30% of the internal needs, it is also going to be included in this study.

Materials used in the European ecoomy-material flow analysis

After carrying out the identification of the critical raw materials with the different approaches specified in the previous sections and the description of their main physical and socioeconomic features, the next objective has been compiling accurate data on availability and material flows for the selected critical raw materials for Europe (EU-28). The main aim is to compare the material flows results using a mass-based and a thermodynamic-based approach. For this endeavor multiple databases, both national and international, have been consulted, such as the mineral statistics from the British Geological Survey (BGS) and the United States Geological Survey (USGS), as well as other reports made by the European Commission and national statistics services from European countries. For the imports and exports, EUROSTAT databases have been used to compile

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information on material trade between EU-28 and the rest of the world, not considering then the internal flows between EU-28 countries.

Using Sankey diagrams, a material flow analysis of the critical material flows in EU-28 has been accomplished for 2014 for the 19 aforementioned mineral commodities. In this type of diagrams, the inputs of the system are represented by imports and production, and the outputs are the exports, recycling and materials consumed within the EU-28. Import and exports data were obtained from EUROSTAT databases, not considering the internal trade between the different countries of the EU-28. As there is no individual recycling rates available for each of the member states of the European Union, average recycling rates for metallic minerals have been used (UNEP 2011).

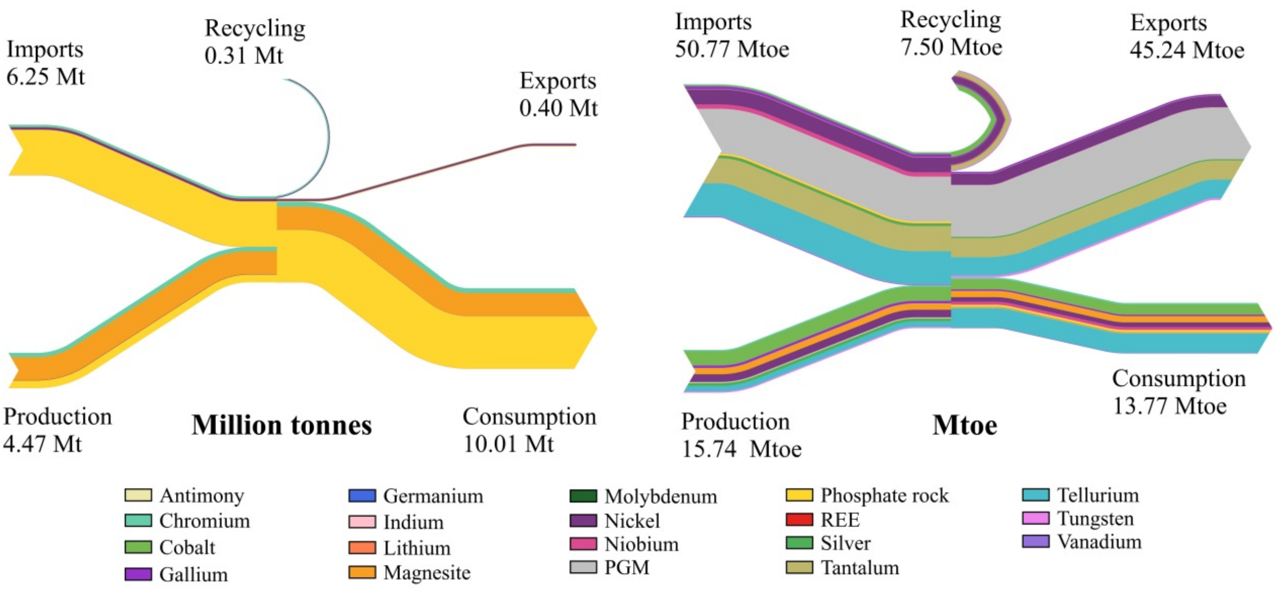

Figure 4. *Sankey diagram of the flows of the materials selected as critical for the EU-28 for 2014 in million tonnes (left) and in Mtoe (right). Data for imports and exports have been collected from EUROSTAT and BGS statistical services.*

For comparative purposes, the diagram has been represented using the information in tonnes (Figure 3, left) and using thermodynamic rarity (Figure 3, right). Even if all the information of the substances selected as critical in this study has been included in the figure, due to their lower values when compared to other substances, both in mass and thermodynamic rarity terms, not all of them can be seen at this scale. Such is the case of gallium, germanium and indium, with smaller production and trade values. Additionally, in the case of tantalum, the trade data (imports and

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exports) that have been used are from British Geological Survey statistics (2016), where they do not differentiate between extra and intra-European trade.

When analyzing the material trade in the EU-28 in mass terms, the minerals that are mostly imported are chromium, nickel and phosphate rock, which in the latter case makes sense as this product is the basis for the agricultural sector and the domestic phosphate rock production is almost negligible when compared to the internal demand. Regarding domestic production, magnesite accounts for 63% of the total share, which is again a product needed for the agricultural and industrial sector. Still, other minerals that are internally produced are chromium and phosphate rock, with a share of 11% and 21%, respectively. As the main materials produced are industrial minerals that are usually neither recycled nor exported, clearly they are used within the EU-28, accounting for the total share of the consumption. In mass terms, recycling and exports contribute only to 6.6% of the total outputs of the system.

On the other hand, if we represent this same information using thermodynamic rarity, expressed in Mtoe, the situation changes drastically. In the case of imports, the minerals that stand out notably are PGM, tellurium, tantalum, nickel and niobium, with shares of 33.7%, 24.7%, 18.8%, 11.0% and 3.2%, respectively. In this case we can see that, even if the imports of those same substances from a mass term perspective seemed less relevant (less than 6% of the total imports), these same numbers expressed in thermodynamic rarity terms can help us to better understand the respective criticality of those substances, as we are taking into consideration other factors such as their scarcity in the crust and in the mines. In the case of domestic production, cobalt, nickel, magnesite and tellurium account for more than 81% of the total domestic EU-28 production. For instance, if we only look at magnesite, we saw that in mass terms that the domestic production accounted for 63% of the total but in rarity terms this number is reduced to only 15%, as magnesium is one of the most common elements found in nature and the energy needed to extract it is not so high when compared to other substances such as tellurium, whose content in the crust is 5 million times lower than magnesium.

Additionally, it is noteworthy the relevance of exports in the outputs of the system when compared to the diagram in mass terms. Exports, that only represented 3.7% of the total outputs in mass terms, when expressed in thermodynamic rarity they account for more than 68%. The main substances exported from the EU-28 in this case are PGM, tantalum and tellurium, minerals whose thermodynamic rarity values are very elevated as seen in Table 1. Even if there are virtually no mines that extract those minerals within the EU-28, there are many processing facilities that integrate smelting and refinery processes whose main final product are precious metals. For

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instance, the smelt-refinery in Antwerp (Belgium), currently produces seven precious metals, being platinum and palladium amongst them, along with other precious and base metals, such as silver, gold, tellurium, indium or REE (Hagelüken and Meskers 2010). Once they are recovered, these products are supplied back into market and exported, even generating a small trade deficit when compared to imports, as is the case of PGM. It is also notable that one of the main importers of palladium in the last few years has been USA, both in unwrought and powered forms.

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Conclusions

This work has incorporated a new dimension in the criticality assessment of raw materials, namely, the thermodynamic rarity approach. As was seen, in combination with the supply risk and economic importance factors usually considered in conventional assessments, it provides additional insights related to the physical aspects of the commodity. Particularly, rarity incorporates two types of costs: first, the embodied exergy (or exergy cost, kWh) of the mineral from mine to market. Second, a hidden cost, understood as the free natural bonus provided by Nature for having minerals concentrated in mines instead of dispersed throughout the crust. The latter is represented by the exergy replacement cost, defined as the exergy cost that would be needed to extract a mineral from ordinary rocks to the conditions of concentration and composition found in the mine, using prevailing technology. From this viewpoint, it stands out that some minerals that have high rarity values are usually not categorized as critical when using only an economic importance and supply risk approach. Still, the energy and ore grade of those substances are properties that could become even more critical in the future.

Consequently, the list of raw materials proposed by the European Commission (EC) in 2014 has been complemented with the rarity dimension. Lithium, niobium, tantalum and tellurium which are not considered critical by the EC are in this new list. Phosphate rock, magnesite, graphite and chromium in turn are not thermodynamically rare, but are relevant from an economic importance and supply risk perspective. This does not mean that they are not critical, but it puts emphasis in the importance of using the three dimensions, thermodynamic rarity, economic importance and supply risk. As a result, a list of 19 critical minerals has been proposed that includes this three dimensions.

With this new list, a Material Flow Analysis for the EU-28 was carried out. To show the physical importance of the raw materials traded, the analysis was additionally performed in rarity terms. This way, one avoids the problem of mixing “apples with oranges” and thereby eclipsing commodities that can be relevant to the economy. For instance, the domestic production of magnesite accounts for 63% of the total internal production when expressed in mass terms, but this number is reduced to only 15% when using thermodynamic rarity. Regarding imports, in mass terms it seems that the only material imported is phosphate rock, with a share of approximately 90%. Yet when analyzing the imports in rarity terms, phosphate rock only accounts for 1.4% and PMG, tellurium, tantalum, nickel and niobium for 91.4%. Thus, using only mass as a yardstick in the assessment reports can generate incomplete results leaving behind other factors such as the physical quality of mineral resources. This way, minerals that were not considered in the critical raw material list but are indeed critical from a physical point of view can be taken into account. Combining both approaches, more accurate and robust resource efficiency policies could be implemented in the European Union putting the focus not only on supply risk and economic importance but also on the quality of the mineral resources that are being considered.

That said, there are other considerations that must be taken into account, such as the reliability of the information on extraction, trade and recycling and the differences found between each statistical service used in the elaboration of the rarity values used in the calculation process. Further efforts should be made to create, verify and unify global and European statistical services with the aim to provide accurate and reliable sources of information.

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