THERMODYNAMIC ACCOUNTING OF THE GLOBAL DEPLETION OF THE MINERAL CAPITAL ON EARTH. A PROPOSAL TO THE U.N.

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ABSTRACT

Thermodynamics can be used as tool for accounting scarcity, unavailability and dispersion of minerals. If a mine is a very improbable occurrence in the Earth's Crust, exergy and its parent concept of replacement exergy cost, could be used and accounted for to make a systematic inventory of the loss of Mineral Capital on Earth. For calculating exergy resources the authors proposed a model of the Planet Earth, namely Thanatia. It hypothetically would consist of a planet totally exhausted of minerals in the crust and completely decimated by climate change in its atmosphere and hydrosphere. Mineral exergy resources are calculated as a function of quantity, composition and ore grade. In this way exergy constitutes a universal, objective and useful tool for assessing resources depletion. Presented over time, it could provide the velocity at which extraction of each and every mineral resource is occurring. The methodology and a case study are briefly presented. The authors propose that the United Nations System of Environmental-Economic Accounting (SEEA) and its global framework would be the best world infrastructure to convert the replacement cost accounts into a Global System of Environmental-Thermo-Economic Accounts (SETEA). In such a way, "Thermodynamic accounting of mineral resources" may play an important role in the global management of the natural resources of the Planet.

INTRODUCTION

The message of Thermodynamics is universal in the sense of it permeates any physical phenomena, but also in the sense of space and time. It covers and explains the whole Planet at any moment in history when time intervals are sufficiently large to reach stabilizations, patterns of change or equilibriums. That is in contrast to transport phenomena sciences like fluid mechanics, or in another realm, finances that describe short time-dependent behaviours.

Economics is a science to live with in the short term. Money is always depreciating and historically no money survived more than the power of the country supporting it. We cannot rely on Economics to have a historical perspective of Man in this planet. Degradation, dissipation, deterioration, entropy, time´s arrow and Second Law are thermodynamic concepts, not economic ones. Notwithstanding, economists, social scientists and policy makers use these terms quite freely and metaphorically, not as an accounting instrument. The global and temporal perspective of our troubled planet can only be understood with the help of Thermodynamics. Thermodynamics is the Economy of Physics.

Two global problems concern responsible men about this planet: Destruction and degradation of ecosystems (biotic resources), and the problem of depletion of mineral resources and materials dissipation in the Planet (abiotic resources).

Our hypothesis is that Thermodynamics can be used as tool for accounting scarcity, unavailability and dispersion of minerals. This approach has not sufficiently considered as an important problem to be studied from a thermodynamic point of view. However, a mine is a very improbable occurrence in the Earth's crust and exergy can be used and accounted for to make a systematic inventory of the loss of Mineral Capital on Earth.

This paper deals with it. It proposes a thermodynamic theory for calculating the annual loss of Mineral Capital on the Earth by using as numeraire, the exergy and replacement exergy cost of mines and minerals.

THE STARTING POINT: THANATIA

The exergy value of any system depends on its intensive properties and the chosen reference environment (RE). Mines, rivers, glaciers, or clouds are natural resources which have exergy. However if we do not care about the reference state, the exergy number one obtains may have nonsense. It is important to distinguish between "exergy" and "exergy resource". In other words, it is critical to choose an appropriate RE to give full sense to the exergy and exergy cost values associated to natural resources.

In 2011, the authors proposed a model of the Planet Earth, namely Thanatia. It hypothetically would consist of a Planet totally exhausted of minerals in the crust and completely decimated by climate change in its atmosphere and hydrosphere. See refs [1] and [2].

Thanatia is a guess thermodynamic model for a terrestrial "grave", where all fossil fuels have been burned and converted into CO2 and with the absence of concentrated mineral deposits. The resulting degraded atmosphere has a carbon dioxide content of 683 ppm and a mean surface temperature of 17ºC. The degraded hydrosphere is assumed to have the current chemical composition of seawater at 17ºC. For the upper continental crust, the authors proposed a model which includes composition and concentration of the 294 most abundant minerals currently found on Earth as bare rocks.

In this sense, Thanatia constitutes a coherent baseline for the assessment of mineral resources in exergy terms. Any substance like mineral deposits or the poles are exergy resources with respect to Thanatia.

Note that Thanatia itself has exergy to some other reference environment like that of the conventional Szargut's RE [3]. Therefore it is not in itself another alternative RE as others profusely published. Thanatia is in fact an imaginary degraded planet that our civilization could smoothly but surely approach, but in the authors hope it will be never reached. (Thanatos means death in Greek). On the other hand, it is a consistent tool sufficient for providing coherent calculations.

EXERGY AND EXERGY COSTS

Once defined the baseline, exergy may be assessed depending on the properties that the resource is considered valuable, such as quantity, composition and ore grade. In this way exergy constitutes a universal, objective and useful tool for assessing resources depletion. Presented over time, it could provide the velocity at which extraction of each and every mineral resource is occurring. The exergy of a mineral resource has at least three components: chemical composition, concentration and cohesion. The chemical exergy of a mineral is equivalent to the minimum energy required to form the minerals from the substances in Thanatia and is given in Eq. 1:

$$b_{ch} = \sum \nu_k b^0_{chel,k} + \Delta G_{mineral} \qquad (1)$$

where $b^0_{chel,k}$ is the standard chemical exergy of the elements that compose the mineral, ν_k is the number of moles of element k in the mineral and ΔG is the Gibbs free energy of the mineral.

Since Thanatia contains virtually every mineral found in the crust, the chemical exergy of the minerals from that reference is zero (as they do not need to be constructed).

As opposed to chemical exergy, concentration exergy expresses the minimum energy required to concentrate the given mineral from the depleted state in Thanatia to the conditions found in the mine (with the specific ore grade). The concentration exergy is calculated with Eq. 2:

$$b_c = -\overline{R}T_0\left[\ln(x_i) + \frac{(1-x_i)}{x_i}\ln(1-x_i)\right] \qquad (2)$$

where R is the universal gas constant (8.314 kJ/kmolK), T_0 is the temperature of the reference environment (298.15 K) and x_i is the concentration of the substance i. The exergy accounting of mineral resources implies to know the ore grade which is the average mineral concentration in a mine x_m as well as the average concentration in the Earth's crust (in Thanatia) x_c. The value of x in Eq. 2 is replaced by x_c or x_m to obtain their respective exergies, whilst the difference between them represents the minimum energy (exergy) required to form the mineral from the concentration in the Earth's crust to the concentration in the mineral deposits.

However, Eq.2 is only strictly valid for ideal mixtures such as solids where there is no chemical cohesion among the substances. But cohesion energy is always present in any mineral. Thus Eq.2 would only strictly remain valid for the exergy of a mixture, and not for the exergy needed to break the binding forces among solids such as hydrogen, hydration, ionic and/or covalent bonds. Such forces are sufficiently strong enough to require physical comminution processes like crushing, grinding, or milling. Therefore, there is an important factor missing in the characterisation, namely the comminution exergy, i.e. the minimum energy required to bind the solids from the dispersed state conditions of Thanatia to those in the mineral deposits. Nevertheless, in [4], the authors demonstrated that comminution is a very energy intensive process when it comes to fine grinding and milling operations but is not so relevant in crushing operations and becomes negligible when evaluating the Mineral loss of Capital on Earth. This is why only the concentration exergy term is taken into account when assessing the Mineral Capital on Earth.

It should be stated though that since exergy is assessed only supposing reversible processes, the numbers obtained are paradoxically far from expected. Hence, we need to complement it with actual exergy costs (kJ), which represent the sum of all *actual* exergy resources that would be required if we were to replace a mineral from Thanatia (or grave) to the conditions actually found in nature (or cradle). This calculation assumes that the same "backup" technologies are applied in the imaginary process from Thanatia to the mine (grave to cradle stage) than in the mine to industry (cradle to gate stage). Therefore Life Cycle Assessments of mining to industry processes become essential for assessing costs, which are calculated with Eq. 3:

$$b^*_{ci} = k_c \cdot b_{ci} \qquad (3)$$

where k_c is a constant called unit exergy cost and is the ratio between the real energy required for the real process to concentrate the mineral from the ore grade x_m to the refining grade x_r and the minimum thermodynamic exergy required to accomplish the same process (Eq. 4).

$$k_c = \frac{E_{realprocess}}{\Delta b_{mineral\, x_m \to x_r}} \qquad (4)$$

Since the energy required for mining is a function of the ore grade of the mine and the technology used, so it is the unit exergy cost.

Then, the exergy cost of concentrating a mineral from the Earth's crust is named exergy replacement cost. Table 1 shows typical values for x_c, x_m, k_c and exergy replacement costs for key minerals.

All proposed concepts, Thanatia, exergy resource and exergy replacement cost are solidly based on the Second Law.

The exergy and exergy replacement costs provide a measure for quantifying this degradation, which is systematically being ignored in conventional accounting systems.

CASE STUDY

As the method provides values in energy units, the annual exergy decrease in the mineral endowment of the planet can now take into account the fossil fuel's exergy plus the losses in nonfuel exergy replacement costs.

As a case study, the exergy replacement costs due to the extraction of minerals in 2008 are explored. The figures reported by the US Geological Survey concerning annual commodity production are considered [5], together with the exergy replacement costs values calculated and shown in Table 1.

According to the authors' calculations, the exergy replacement costs associated to the 2008 production of the studied minerals is equal to 5.3 Gtoe. It is worth to note that conventional economics only accounts for the energy required in the extraction and refining processes. In the case of the materials studied, these account for around 9% of the total world fossil fuel produced in year 2008 (see Fig. 1).

Nevertheless a fair accountability of resources should also take into account the use and the decrease of the non-fuel mineral capital endowment. This means that the true yearly balance of the exergy decrease in the mineral endowment of the planet should account for at least, the exergy of fossil fuels world production plus the loss of the mineral exergy replacement costs of the non-fuel minerals. As can be seen in Fig. 2, this accounts for 32% of the whole energy stages, if the cradle to grave stage is taken into account. This is a considerable and unexpected percentage since it has the same order of magnitude as the yearly loss of coal, oil or natural gas.

But these minerals are not lost at all. Only those that are not recycled and are not in use (in-use-stock) become really lost. Considering the same recycling ratios for the whole world as in the US [5], means that from the total exergy replacement costs of the minerals extracted, only 72% is either lost or yet in use, i.e. around 3.8 Gtoe. Unfortunately only mass consumable metals like steel, aluminium, copper and few others are recycled in rates no greater than 50-60% worldwide The same happens with precious metals[6]. Adding the exergy of the fossil fuels used in the extraction and processing of the minerals, we obtain that the total exergy expenditure due to mineral production in 2008 was equal to 5.3 Gtoe. It should be stated that only 37 minerals have been considered.

Hence, the previous reported value would increase, if all mineral commodities were to be included in the analysis.

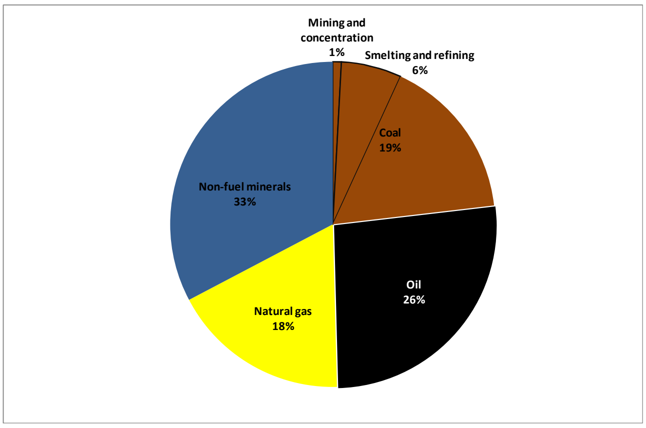

Fig 2: Distribution of the exergy costs associated to the 2008 world production of the main mineral commodities

FROM SEEA TO A GLOBAL SYSTEM OF ENVIRONMENTAL-THERMO-ECONOMIC ACCOUNTS.

The depletion of a mineral should not be more the difference between its world price and its economic cost of production as economists propose. On the contrary, it should be assessed as the loss of reserves quantified through its replacement cost with current best available technologies, from the bare rock to the ore grade conditions of the mine. This depletion indicator can be used for all fossil fuels and minerals no matter their chemical composition and concentration. Fossil fuels must be replaced with renewable energy sources and this replacement need to be accounted for such progress. In the same way, stopping depletion of metals will largely come from greater resource-efficient techniques such as designing for recyclability, reducing the number of alloys used, avoiding the design of monstrous hybrids, [7] designing for disassembly, symbiosis of industrial complexes, increasing the efficiency of smelters to avoid metal losses in slags, increasing the throughput of scrap, etc.[8].

Conservation means, in fact, avoided replacement. Actually, the cost of replacement is a mind barrier for hampering deliberate destructions. Indeed, one can associate a cost of replacement to each and every conservation act, not only to mineral resources but, more in general, to any natural resource. The more irreplaceable an object is the stronger will be the need for its conservation. Irrecoverability would need ethernal conservation. Accounting replacement costs is accounting our debt with future generations.

On the other hand, valuing technological improvements is as important as conservation of resources. An essential fact is that replacement costs using the "best available or back-up technologies" decrease as much as knowledge improves. The evolution of replacement costs of natural resources is a straightforward and quantitative indicator of technological achievements. Therefore, if the evolution of best available technologies is a reflex of increased embodied knowledge, one should see to what extent it decreases the debt owed to future generations. Nevertheless, it is not clear that any new technology, both directly or indirectly, improves efficiency in production processes, and thus diminishes the negative balance of the current generation. This is because of the rebound effect, in which better resource efficiencies may lead to increased resource usage. Anyhow, the concept of replacement cost apprehends both ideas: conservation and technological improvements.

Yet conservation goes beyond repair, restoration, or replacement. It is a value that requires a change in lifestyle brought about through education. Education is an indispensable tool not just in terms of conservation but also in the learning of technological innovation. Education systems must cope with both. In fact, an intense tech oriented society should need to be counterbalanced with a deep sense of conservation. Consequently, as Snow (1959) proposed, the Second Law of Thermodynamics ought to be placed at the core of literacy classes[9].

If replacement can be calculated and registered for almost any action of Man on the planet, an international framework to provide concepts, definitions, classifications, accounting rules and standard tables for all countries could be built. The System of Environmental-Economic Accounts (SEEA) of the United Nations may well provide such statistical framework [10]. The System of National Accounts (SNA) is an established system for producing internationally comparable economic statistics which imposes the organization and standardization of domestic accounts. It is widely accepted and established worldwide. Bureaus of statistical office (BSO) for data recovering and economic accounting exist in almost any country. Companies and countries report economic and physical data following the established accounting procedure and BSOs integrate them. It is a huge infrastructure. From households to companies and to countries, these accounts are

presented in monetary values with the SEEA following the accounting structure of the SNA and thus facilitating the integration of environmental statistics with economic accounts. Each national BSO needs to take responsibility for the environmental data recovery and environmental-economic accounting practice. Unfortunately the information recovered by the physical tables needed for SEEA is rather poor since simply registering material tonnage is not sensitive enough for qualifying most of the physical phenomena.
The aggregation level of accounting determines the numeraire to be used in the accounts. Monetization runs well from households to companies. At the countries level the money yardstick is proved insufficient for economic-environmental accounts whilst at the aggregated global level accounts, money losses weight in favour of physical accounts. Furthermore, for the proper viewing of the planet's evolution, monetary accounting is not only insufficient but inappropriate.

Replacement is the keyword for accounting the remaining planetary global resources. What is the cost of replacing those natural resources our society destroys? We lack costing accounts even though technology and enjoyment of life are the benefits. Technology increases knowledge at the cost of natural resources, but technology may be used either for improving its productivity or for destroying them quicker. There is a need to raise the awareness that it is now possible to put numbers to this debate. This can be done just using the Second Law of Thermodynamics through the exergy and exergy cost measured in S.I. units as a numéraire. The cost of replacement of non-renewable resources and the cost of restoring deteriorated renewable resources may be used to account how much effort our society should need to close the natural and man-made cycles. Having this accounting knowledge, the doors are open for a global managing of natural resources. This knowledge could induce efforts to pay some of the debt, even though many others will remain as a debt to future generations. These generations will thank these accounts. As the former Deputy Secretary-General of OECD, B. Ásgeirsdóttir [11] said *"the luxuries of one generation are often the needs of the next "* and, *" We need to achieve more sustainable consumption and production patterns, to increasingly decouple environmental pressure from economic growth, to ensure sustainable management of natural resources, and to work together in partnership to reduce poverty"*.

The United Nations System of Environmental-Economic Accounting and its global framework would be the best starting point for achieving these accounts. To do this the SEEA would need another step forward to convert them into a Global System of Environmental-Thermo-Economic Accounts (SETEA). In the same way that the System for National Accounts has smoothly evolved into the SEEA, someday it would be possible to have complementary accounts for natural resources replacement costs into the framework of SEEA. A major intellectual effort needs to be done from the concepts stated here. At the end, the real overall accounting unit will be the residence time of the human species on the planet.

For making a solid proposal, we have already developed the thermodynamic tools for minerals, water, natural resources. But the way to go is too long for only one research group. JETC could be a good platform for discussing such project and launch a truly European/international proposal to UN in this way."

CONCLUSIONS

The power of thermodynamics is simply fascinating to give answers to ecological problems when thinking in a very broad perspective: temporal, (i.e. historic), and spatial, (i.e. planetary level).
In our view, Thermodynamics may still play an important role in managing our planet´s resources. We think "Thermodynamic Accounting" may count in a global management of the natural resources of the Planet. Ecology could receive an important intellectual support, and economists could better understand the need for planning and caring today what could happen in the near long term, beyond several generations. Just converting ideas into numbers one can go beyond the debate between techno-optimists and techno-pessimists and provide real tools for a rational management of the Mineral Capital on Earth.

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	xc[g/g]	xm[g/g]	k(x=xc)	Exergy replacement costs	Mining and conc.	Smelting and refining
Al-Bauxite (Gibbsite)	1.38E-03	7.03E-01	2088	627	11	24
Antimony (Stibnite)	2.75E-07	5.27E-02	3929	474	1	12
Arsenic (Arsenopyrite)	4.71E-06	2.17E-02	1470	400	9	19
Beryllium (Beryl)	3.22E-05	7.80E-02	362	253	7	450
Bismuth (Bismuthinite)	5.10E-08	2.46E-03	7859	489	4	53
Cadmium (Greenockite)	1.16E-07	1.28E-04	39230	5898	264	279
Chromium (Chromite)	1.98E-04	6.37E-01	48	5	0	36
Cobalt (Linnaeite)	5.15E-09	1.90E-03	-	10872	9	129
Copper (Chalcopyrite)	6.64E-05	1.67E-02	525	110	29	21
Fluorite	1.12E-05	2.50E-01	582	183	1	-
Gold	1.28E-09	2.24E-06	6380357	583668	107752	-
Gypsum	1.26E-04	8.00E-01	118	15	0	-
Iron ore (Hematite)	9.66E-04	7.30E-01	165	18	1	13
Lead (Galena)	6.67E-06	2.37E-02	384	37	1	3
Lime	8.00E-03	6.00E-01	13	3	0	6
Lithium (Spodumene)	3.83E-04	8.04E-01	190	546	13	420
Manganese (Pyrolusite)	4.90E-05	5.00E-01	37	16	0	57
Mercury (Cinnabar)	5.73E-08	4.41E-03	209116	28298	157	252
Molybdenum (Molybdenite)	1.83E-06	5.01E-04	6505	908	136	12
Nickel (sulphides) Pentlandit	5.75E-05	3.36E-02	13039	761	15	100
Nickel (laterites) Garnierite	4.10E-06	4.42E-02	876	167	2	412
Phosphate rock (Apatite)	4.03E-04	5.97E-03	77	0	0	5
Potassium (Sylvite)	2.05E-06	3.99E-01	1926	1224	3	N.A.
REE (Bastnaesite)	2.54E-03	8.11E-02	588	31	10	374
Silicon (Quartz)	2.29E-01	6.50E-01	6	1	1	76
Silver (Argentite)	1.24E-08	4.27E-06	112846	7371	1281	285
Sodium (Halite)	5.89E-04	2.00E-01	71	44	3	40
Tantalum (Tantalite)	1.58E-07	7.44E-03	6729367	482828	3083	8
Tin (Cassiterite)	2.61E-06	6.09E-03	2704	426	15	11
Ti-ilmenite	4.71E-03	2.42E-02	172	5	7	128
Ti-rutile	2.73E-04	2.10E-03	143	9	14	244
Uranium (Uraninite)	1.51E-06	3.18E-03	13843	901	189	N.A.
Vanadium	9.70E-05	2.00E-02	4174	1055	136	381
Wolfram (Scheelite)	2.67E-06	8.94E-03	69721	7429	213	381
Zinc (Sphalerite)	9.96E-05	6.05E-02	104	25	1	40
Zirconium (Zircon)	3.88E-04	4.02E-03	10580	654	739	633

Table 1: Exergy replacement costs of key minerals compared to conventional costs of mining and concentrating and smelting and refining. Values are in GJ/ton if not specified.

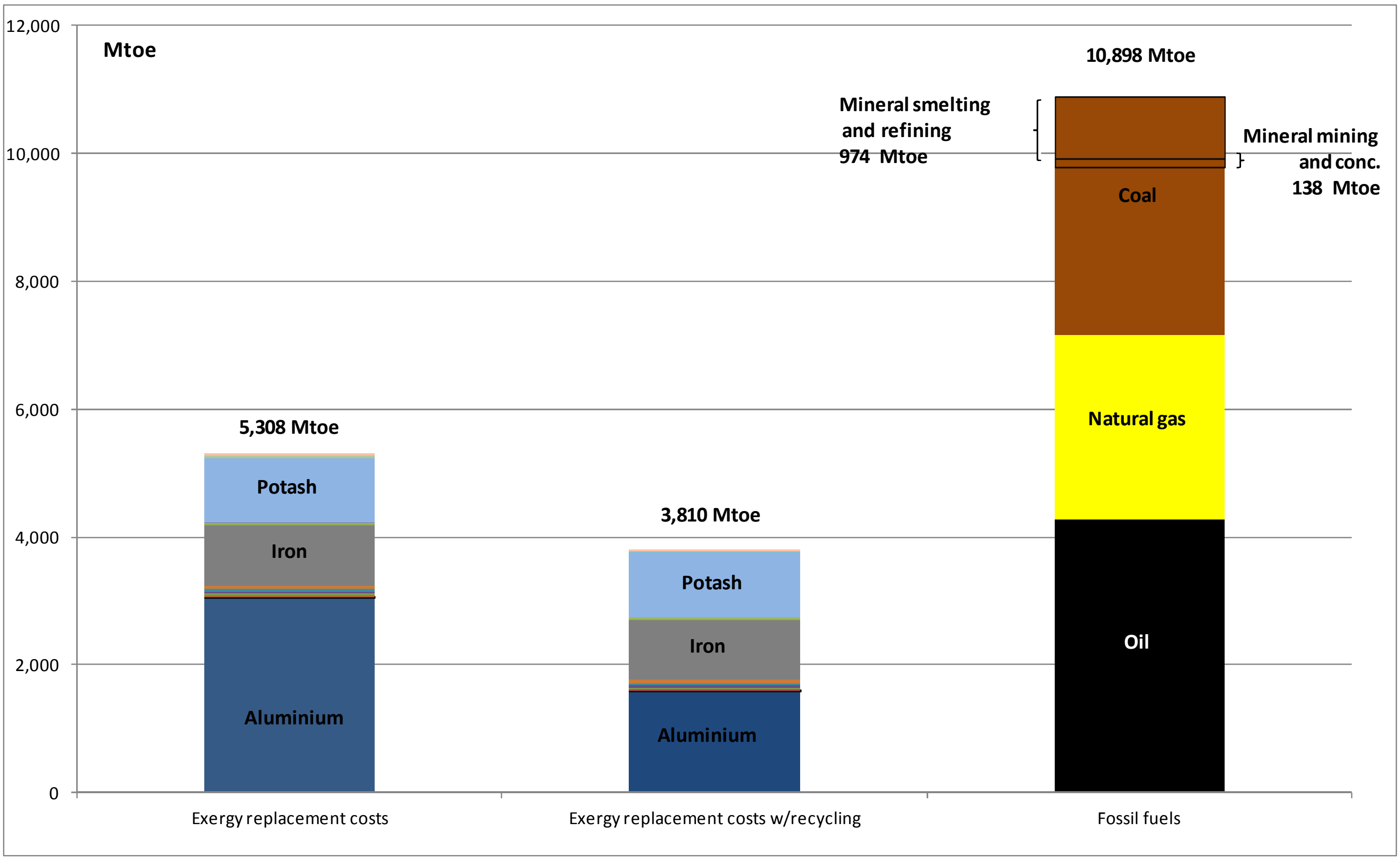

Fig. 1: Exergy replacement costs associated with the extraction of mineral commodities in 2008.