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# New method to compute the emergy of crustal minerals

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ABSTRACT

To date, Unit Emergy Values (UEVs) for crustal minerals (e.g. limestone, iron ore, etc.) have lacked thermodynamic basis and suffer from overly vague generalization (relative to most other, more certain emergy indicators). We assume a steady state crustal cycle that embodies the various forms of exergy supporting Earth system cycles. The UEV of average crust is 1.75E+09 solar emergy joules per gram (specific emergy). The ratio of crustal specific emergy to a mineral's exergy density (exergy per mass) is the mineral's transformity. This is an important assertion as it is the dissipation of exergy which hierarchically organizes materials. Emergy accounting should be able to express every resource either a transformity or specific emergy, linked by exergy density; crustal minerals are no exception.

Mineral transformity can be characterized using either chemical exergy or Gibb's formation energy. Both calculations use the same mixing term which depends on average crustal abundance of the mineral. Also it's possible to account mineral emergy using either total free energy (or total chemical exergy) or by accounting only the mixing exergy. Four herein proposed methods yield a wide range of specific emergies for each of the prominent mineral/metal inputs to economies. We conclude that the exergy of concentration (mixing exergy) best represents that which is destroyed in mining/extraction activities and that using Gibb's transformities better suit the emergy method due to chemical exergies being positive or negative depending on the mineral. The emergy accounting of minerals should utilize Gibb's transformities and account only the emergy of a mineral's mixing exergy because this represents the natural capital that is irrevocably destroyed in mineral harvesting.



## 1. Introduction

Exergy means *available potential energy*. Exergy is "the amount of work obtainable when some matter is brought to thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above-mentioned components of nature" (Szargut et al., 1988). Emergy is a measure of all degraded exergy, from a predefined time origin, which contributed to generating a 'given system' under consideration (Giannantoni, 2002).

Sunlight is the most practical unit for emergy because it's the most abundant and evenly distributed exergy source to the Earth system. Thus Earth emergy is expressed as solar emergy joules (seJ). The two other important independent exergy sources to the Earth are deep earth heat and the gravitational potential energy of the Earth-Moon-Sun system. This tripartite of exergy sources are expressed as equivalent sunlight exergy based on their joint work accomplished in the steady state geobiosphere (Brown and Ulgiati, 2010). The sum of the tripartite is the geobiosphere emergy baseline (GEB; 15.2 $E+24$ seJ/yr).

When concentrated materials disperse to ambient abundances, heat and entropy are generated (Faber, 1984). A concentration gradient is thus a storage of available potential energy (a.k.a. exergy). The cumulative exergy of one form dissipated to create a concentration gradient is the gradient's emergy. The ratio of this gradient's emergy to its exergy is named transformity (seJ/J). Transformity offers a hierarchical perspective of energy quality (Giannantoni, 2002) in the geobiosphere. Quality indicates the donor-, or supply-side perspective (i.e. what is required from the environmental for genesis) of an exergy's ability to induce useful work (utility) in the geobiospheric system (Odum, 1996). A storage's emergy divided by its useful mass is called specific emergy (seJ/g). Specific emergy indicates material quality and is linked to transformity via specific exergy (J/g). Specific emergy and transformity, by definition, jointly characterize resource quality. They are collectively referred to as UEVs (unit emergy values).

*Abbreviations:* Ga, Giga-annum, i.e. one billion years; GEB, geobiospheric emergy baseline; ME, mass enrichment method; NEAD, National Emergy Accounting Database; RE, reference environment; UEV, unit emergy value.

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A driving question for this research is how to relate crustal mineral specific emergy to changes in concentration *and* changes in specific exergy? Presently crustal material emergy is accounted by mass, rather than by exergy, because accounting mass is more familiar and more common in the emergy literature, and mass is easier to handle with available computation methods. Flaws of these methods will be discussed, after which we present the calculation procedure to produce unique UEVs for crustal minerals. Lastly we apply these new UEVs to the emergy accounting of the US mineral consumption in 2008, and compare the results with previous analyses.

### 1.1. *Previous estimates of crustal mineral emergy*

Various tectonic (Odum, 1996; Table 3) and sedimentary processes (Odum, 2000a; Table 1) were evaluated as co-products of the GEB. Co-product assumption is like a black-box where the internal pathways of crustal genesis are unknown. The same source exergy is attributed to each co-product (there are several). Because co-products embody the same source exergy they shouldn't be added in a resource accounting analysis to avoid double counting the sources. The emergy of sedimentary (e.g. limestone, evaporites) and tectonic (e.g. granitic rocks, metamorphic rocks, etc.) rocks embody the same exergy (i.e. the GEB). Actually, approximately 10% of 2008 US metal/mineral emergy is double counted for this reason (Table 1).

Odum (1999, 2000b) estimated a linear relation between the specific emergy of lead (Pb) and its concentration. This relation results from topological emergy methodology (i.e. ore grade assumed to be directly, and linearly, related to environmental support of ore body creation). Topological emergy enrichment was extended to all crustal elements (Cohen et al., 2007) validated against economic relations with ore grade. Copper ore tonnage was negative $\log_{10}$ correlated with ore grade, a phenomenon consistent across crustal elements (Ibid.). Thus ore body specific emergy (for all crustal elements) was assumed linearly related with purity. This mass enrichment (ME; Ibid.) method is the most commonly applied method to compute the emergy of crustal materials (e.g. Rugani et al., 2011; Brown et al., 2009) but a thermodynamic link relating mass and exergy and thus specific emergy and transformity is still missing.

Every other resource in emergy accounting has both a transformity and specific emergy. This assertion is not readily evident because many resources are almost always expressed as either a transformity (e.g. sunlight, wind, fossil fuels, etc.) or specific emergy (e.g. metals, minerals, fertilizers, etc.). It's possible, though impractical, to express sunlight as mass or fertilizer as chemical exergy which makes possible the expression of their specific emergy or transformity respectively. All transformities are the ratio of a resource's emergy to its intrinsic exergy. It is the dissipation of exergy which carries materials along the energy hierarchy, where such materials are organized into material hierarchies (Odum, 1999). Thus exergy links the energy and material hierarchy, represented by transformity and specific emergy respectively. The general relationships are as follows:

$$\tau = {}^{\varepsilon}\!/\!_{\beta} \quad (1)$$

$$\varepsilon = \tau\beta \quad (2)$$

$$\beta = {}^{\varepsilon}\!/\!_{\tau} \quad (3)$$

Where, transformity, $\tau$ (seJ/J), is linked to specific emergy, $\varepsilon$ (seJ/g), through specific exergy, $\beta$ (J/g). A linear relation between specific emergy and transformity is possible only if specific exergy is a linear function. As shown later, specific exergy of minerals is a non-linear function of molecular purity.

Martinez et al. (2007) argued for the exergeocology method, as opposed to the emergy method, focussing on the chemical and concentration exergy of minerals (discussed later). They characterize mineral value with the combination of these two exergies along with mineral exergy replacement cost, which is the exergy required to remake the properties of a mineral deposit by means of human technology. Mineral exergy, in this way, is defined as the minimum energy required to remake a deposit from the reference environment (RE) via a reversible process. Crustal exergy can then be tallied along with other resource exergies (e.g. fossil fuels, water kinetic, etc.) in life-cycle-assessment as an exergy-based impact assessment method (Valero and Valero, 2012; DeWulf et al., 2008).

De Vilbiss (2013) utilized external energy needed to concentrate a mineral to characterize a 'transformity' enrichment factor. Methodologically, this approach had many flaws, discussed later, but it made possible the innovations of the current work. Jamali-Zghal et al. (2014) explored integrating exergoecology with emergy to underscore crustal specific emergies; however their analysis had several flaws. For example, the average transformity of the crust was determined to be the weighted average transformity of Earth's tripartite (Table 1, Ibid.). As shown later, average crust transformity (seJ/J) is the emergy of the crust divided by the exergy of the crust. Further, the analysis summed a mineral's exergy replacement cost with its intrinsic chemical and concentration exergies. Mineral exergy replacement cost is a measure of human investment needed to remake an ore deposit, which is far from optimum as evidenced by humanity's rapidly evolving technological efficiency. Exergy replacement cost is not a characteristic held by the mineral itself and therefore adding it with chemical and concentration exergy fallaciously inflates a mineral's potential to do work (i.e. its exergy).

**Table 1**
Most important metal and mineral emergy inputs in 2008 to the US economy (data from NEAD, 2014).

| Item | Mass (2008 MT) | Specific emergy (seJ/g) | Emergy (2008 E ± 22 seJ) | % tot. (%) | Type | Mass enrichment or source[a] | Mean crustal abundance mg/kg | Mine crustal abundance mg/kg |
|---|---|---|---|---|---|---|---|---|
| Limestone | 885203000 | 9.50E+09 | 841 | 83 | Mineral | Limestone | | |
| Dolomite | 59400000 | 9.50E+09 | 56 | 6 | Mineral | Limestone | | |
| Iron ore | 54000000 | 5.78E+09 | 31 | 3 | Metal | 3.4 | 56300 | 193780 |
| Lead | 423000 | 4.80E+11 | 20 | 2 | Metal | 285.7 | 14 | 4000 |
| Phosphate rock | 30900000 | 6.45E+09 | 20 | 2 | Mineral | 3.8 | 1050 | 3990 |
| Copper | 1310000 | 9.80E+10 | 13 | 1 | Metal | 58.3 | 60 | 3500 |
| Gypsum | 12700000 | 9.50E+09 | 12 | 1 | Mineral | Limestone | | |
| Zinc | 778100 | 7.20E+10 | 6 | 1 | Metal | 42.9 | 70 | 3000 |
| Molybdenum | 61400 | 7.00E+11 | 4 | 0.4 | Metal | 416.7 | 1.2 | 500 |
| Cadmium | 745 | 3.36E+13 | 3 | 0.2 | Mineral | 20000.0 | 0.15 | 3000 |

[a] Mass enrichment means the ratio of mine grade to average crustal abundance.