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► To cite this version:

Nadia Jamali-Zghal, Olivier Le Corre, Bruno Lacarrière. Mineral resource assessment: Compliance between Emergy and Exergy respecting Odum's hierarchy concept. *Ecological Modelling*, Elsevier, 2014, 272, pp.208-219. <10.1016/j.ecolmodel.2013.09.017>. <hal-00879451>

HAL Id: hal-00879451

<https://hal.archives-ouvertes.fr/hal-00879451>

Submitted on 4 Nov 2013

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Mineral resource assessment: Compliance between Emergy and Exergy respecting Odum's hierarchy concept

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Abstract

In this paper, authors suggest to combine the exergoecology and the emergy concept in order to evaluate mineral resources, taking into account their abundance, their chemical and physical properties and the impact of their extraction. The first proposition of this work is to consider that every group of mineral, dispersed in the Earth's crust, is a co-product of the latter. The specific emergies of dispersed minerals are, then, inversely proportional to their abundance. The results comply with the material hierarchy as the specific energy of a dispersed mineral rise with its scarcity. The second is an emergy evaluation model based on the chemical and concentration exergy of the mineral, its condition in the mine and its abundance. This model permits to assess the decline of mineral reserves and its impact on the ecosystem. The dispersed specific energy of 42 main commercially used minerals has been calculated. Furthermore, the emergy decrease of some Australian mineral reserves has been studied, as well as the land degradation of US copper mines.

Keywords: Emergy, Exergoecology, Mineral resource depletion, Material hierarchy

1. Introduction

Emergy can be considered as an "energy footprint" which memorizes all energies in their original forms, converted in solar energy (seJ, Solar emjoule), consumed or transformed to create a product or a service (Odum, 1996). As the production complexity and the ability to do work can be very different from one form of energy to another, the emergy concept posits that the energy flows of the universe are organized in an energy

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27 transformation hierarchy (Odum, 1996; Brown and Ulgiati, 2004). The position of any
28 kind of energy in this hierarchy is given by its transformity which is by definition, the
29 ratio between the emergy contribution (input) and the exergy (output). While assum-
30 ing that the real wealth of the environment is the work of the geobiosphere, the annual
31 emergy flow of the geobiosphere is considered to be the baseline reference from which
32 all other unit emergy flows are directly or indirectly derived from (Odum, 2000b; Brown
33 and Ulgiati, 2010).

34 To evaluate mineral resources Odum proposed what he called '*the 6th energy law*'
35 (see Citation 1) to relate material cycles to the energy hierarchy concept, which permits
36 to classify hierarchically materials from the point of their specific emergies (seJ/g).
37 The emergy concept posits that the universe is hierarchically classified, describing the
38 diminution of available energy with each transformation process. The transformity,
39 defined as the emergy driving the process per unit of available energy, indicates the
40 position of any transformation process in the hierarchy, since the latter enhances the
41 quality of the produced energy but reduces the amount of available energy. Thus, the
42 greater the transformity is, the more available energy of a lower level of the hierarchy
43 has been involved in the transformation process. The same reasoning can be applied
44 to material cycles: the concentration of dispersed minerals requires available energy
45 i.e. the higher the concentration of the mineral deposit is the more available energy
46 has been downgraded and the higher the emergy per mass should be. Otherwise, when
47 concentrated minerals becomes dispersed, available energy is lost and the stored emergy
48 diminishes.

49 **Citation 1 (*An energy hierarchy law for biochemical cycles*)**

« *Materials of biochemical cycles are hierarchically organized be-
cause of the necessary coupling of matter to the universal energy
transformation hierarchy* » (Odum (2000a))

50

52 Previous studies (Cohen et al., 2007; Brown, 2007) have been carried out to evaluate
53 the emergy of mineral resources, expecting that the specific emergy of a mineral reserve

54 em_R varies linearly with its enrichment factor EF_R , see Equation 1.

$$em_R = B_R \cdot EF_R \quad (1)$$

55

56 Cohen et al. (2007) and Brown (2007) used both an enrichment factor based on
57 the ore grade cutoff OGC and the crustal concentration $x_{M_{cr}}$ of the mineral, which is
58 by definition the minimum ore grade a mine should have to be exploited profitably.
59 The value is very variable, it depends essentially on the current level of technology and
60 the market demand of the mineral. An universal baseline B_R was applied because the
61 different rock types from which the minerals are extracted, are considered to have little
62 varying specific energies. Cohen et al. (2007) first, used the specific energy of land
63 cycle (calculated by Odum (1996)) as baseline. Brown (2007), later, updated this work
64 by adopting the specific energy of the Earth's crust that he calculated. In addition,
65 a regression model relating the cutoff concentration to the price and abundance has
66 been elaborated to estimate the specific energy of those minerals for which the cutoff
67 concentration were not available. The results of these studies, however, as they are
68 based on the ore grade cutoff of the mineral, do not represent the real energy that
69 Nature invested to create the mineral reserve, but rather an evaluation in view of
70 standards set by society, because the results only reveals the minimum specific energy
71 a reserve should have to be beneficially extracted. Besides, integrating market prices
72 to estimate the specific energy of ore deposits seems not to be an adequate solution
73 because the prices rarely vary with the condition of the mineral in the mine but often
74 with economic, financial and geopolitical circumstances. Thus, the highest specific
75 energy obtained by this approach do not correspond to scarce materials as expected
76 by Odum who emphasized in his book that scarce minerals require more work for their
77 creation and concentration (see Citations 2 and Citations 3), but to those with high ore
78 grade cutoffs. This shows that the evaluation of mineral resources by this method is
79 limited in particular because the chemical composition and the decline of the reserves

80 is not taken into account.

81 **Citation 2 (*Environmental accounting*)**

82 *« Energy per unit mass (seJ/g) indicates the position a mineral
has on the scale of Earth scarcity and unit value. » (Odum (1996),
p.121)*

84 **Citation 3 (*Environmental accounting*)**

85 *« In general, the scarce products from the Earth are those that
required more work for their formation and concentration. There-
fore they tend to have higher Energy contents. Burnett (1981)
found that materials with more energy contribution were less abun-
dant. » (Odum (1996), p.117)*

87 Several scientists even goes further in their criticism, claiming that contrarily to
88 exergy analysis, energy evaluation is not suitable to assess mineral resources. Martinez
89 et al. (2007) concluded, after comparing the evaluation of Earth's mineral resources via
90 both energy and exergy analysis that the latter method is more adequate for accurate
91 mineral valuation. Sciubba (2010) stated that energy accounting is unable to evaluate
92 the degradation of mineral resources caused by human consumption, see Citation 4.
93 As well as Valero et al. (2008) who contested the rigorousness of mineral resource
94 assessment via energy analysis, see Citation 5.

95 Actually, when exergy analyses are used to evaluate natural capital, it should be
96 kept in mind that exergy is a state function. Thus, it does not describe the processes
97 that generated natural capital, but only the results of theses processes i.e. the distance
98 from their thermodynamic equilibrium, without any consideration for the followed path
99 and for the origin of the required energy. It can therefore be concluded that the exergy
100 method permits to assess accurately the energy required to replace mineral resources
101 with present technology but that it is unable to evaluate the work that was done by
102 Nature to form ore deposits.

103 The aim of this paper is to combine the emergy and the exergy approach, in order
 104 to evaluate the real wealth of mineral resources, taking into account their physical and
 105 chemical conditions and the driving forces behind their evolution. This work try to
 106 develop a methodology that permits not only to quantify the quality decrease of ore
 107 deposits during mining but also to illustrate the impact caused by mineral extraction
 108 and the work that should be done to restore the post-mining land.

109 **Citation 4 (*On the Second-Law inconsistency of Emergy Analysis*)**

«It is recommended therefore that Emergy Analysis be not used
 to assess the global resource consumption caused by anthropic ac-
 tivities, because its results are misleading when it comes to estimate
 the exergy destruction enacted by real industrial transformations.»
 (Sciubba (2010))

110

112 **Citation 5 (*Exergy evolution of the mineral capital on earth*)**

«No matter how much solar energy is received from the sun,
 the quantity of gold or iron for instance on Earth, will not change.
 Consequently, the rigorousness of the transformities for mineral re-
 source assessment is doubtful.» (Valero et al. (2008), p.8)

113

115 **2. Methodology**

116 *2.1. Scope of the study*

117 The production of non-fuel minerals for economic use involves a series of physical and
 118 chemical processes, see Figure 1. These complex processes are either natural or man-
 119 made, therefore it is recommended to distinguish between natural and anthropogenic
 120 exergy in assessing mineral resources. The minerals' natural exergy represents the effort
 121 invested by Nature to create them with their chemical and physical properties as they
 122 are found in the mine. The minerals' anthropogenic exergy, however, represents the
 123 energies that should be mobilized by man to make the mineral suitable for commercial

124 use.

125 In this work only the natural exergy of the mineral has been studied with the aim of
126 quantifying the environmental impact of mineral resource depletion.

127 *2.2. Exergy analysis of non-fuel mineral reserves*

128 Minerals are limited, non-renewable natural resources offered by Nature and ex-
129 ploited by human society. Any natural resource is characterized by its specific com-
130 position and concentration, which distinguish it from its environment. These intrinsic
131 properties permit to measure the thermodynamic value of a natural resource, called
132 material's exergy (Riekert, 1974), which is defined as the minimum theoretical work
133 that Nature should invest to produce it with its specific structure and concentration. A
134 number of exergy-based approaches have been proposed to evaluate natural resources.
135 The most common concept may be the Thermo-ecological cost analysis introduced by
136 Szargut et al. (2002). This method proposes to measure, in terms of exergy and energy,
137 the ecological cost of non-renewable natural resource depletion. Therefore the cumula-
138 tive consumption of non-renewable exergy connected with the fabrication of particular
139 products, including the abatement processes of the resulting emissions and wastes is
140 accounted for. The exergoecology approach, introduced by Valero (1998) and used in
141 this study, differs fundamentally from Szargut's method as it is not interested in the
142 exergy costs of the production processes but rather on the physical cost that would be
143 required to produce, with today's best technology, natural resources from its compo-
144 nents in a defined reference environment (which is assigned as the most degraded state
145 of the resource) to the physical and chemical conditions as they are found in Nature.
146 This thermodynamic tool permits to provide a realistic value of the energy that Nature
147 stored in form of concentrated mineral resources and that will be irreversibly lost when
148 these minerals are used up. It should be noted that the exergoecology should not be
149 confused with with the eco-exergy concept, introduced by Jorgensen (2006) and applied
150 to measure the development and health of an ecosystem

151 *2.2.1. Exergy of non-fuel minerals*

152 In this work, the thermodynamic evaluation of minerals is based on Szargut's refer-
 153 ence environment methodology (Szargut et al., 2005). The chemical composition and
 154 the thermodynamic properties of this hypothetical environment permits to calculate
 155 the theoretical minimum work that must be invested to reproduce from the reference
 156 substances the composition of the Earth crust, in form of a homogeneous solid layer
 157 where all minerals are uniformly distributed at their average concentration $x_{M_{cr}}$. The
 158 reference environment is considered as a source of heat and reference substances. The
 159 process is assumed to be reversible. The mineral's specific chemical exergy ex_{chM} can
 160 be calculated by using the exergy balance of a reversible reaction, as the reference sub-
 161 stances are supposed to be at a standard ambient temperature and pressure and stan-
 162 dard concentration in the natural environment (Szargut, 1989; Valero et al., 2002a), see
 163 Equation 2.

$$ex_{chM} = \Delta g_f + \sum_i y_i \cdot ex_{chi} \quad (2)$$

164

165 Δg_f represents the specific Gibbs free energy of mineral M and y_i and ex_{chi} are
 166 respectively the molar fraction and the specific chemical exergy of component i of
 167 mineral M .

168 Ore deposits are naturally occurring aggregates of minerals, their ore grade repre-
 169 sents the mineral content of the rock which is much higher than the average concen-
 170 tration of the mineral in the Earth's crust. Concentrated minerals in mines can be
 171 easily extracted with present technology, compared to other parts of the Earth's crust
 172 where the mineral is dispersed. Thus, according to Szargut's reference environment
 173 methodology, any mineral resource with higher concentration would have an amount
 174 of energy provided by Nature, which differentiate it from its dispersed state in the ref-
 175 erence environment. The concentration exergy is defined by Valero et al. (2009) to be
 176 the minimum required work to concentrate, in a reversible way, the dispersed mineral

177 in the Earth's crust into mines. Assuming, that an ore deposit is an ideal mixture
 178 of a mineral M and rock, the specific concentration exergy of the mineral ex_{cM} can
 179 be equated to the minimum amount of work that should be furnished to separate the
 180 mineral (concentrated at x_M) from the rock, see Equation 3. It can be seen that the
 181 higher the ore grade, the lower the effort needed to extract the mineral from the mine,
 182 pointing to the fact that concentrated minerals represent a natural energy contribution,
 183 easing its extraction.

$$ex_{cM}(x_M) = -RT^\circ \left\{ \ln(\lambda_M x_M) + \frac{(1 - \lambda_M x_M)}{\lambda_M x_M} \ln(1 - \lambda_M x_M) \right\} \quad (3)$$

184

185 Where R represents the universal gas constant, T° the standard ambient temper-
 186 ature and λ_M the molar mass ratio between the mineral and the mixture of rock and
 187 mineral.

188 Valero identifies three theoretical states of mineral evolution to calculate the exergy
 189 that should be invested to form mineral deposits from the reference environment, see
 190 Figure 2:

191 1. State 0 (Reference environment): All the reference substances are dispersed,
 192 mixed and in thermodynamic equilibrium \Rightarrow The exergy is Zero.

193

194 2. State 1 (Dispersed minerals): Chemical reactions took place, the minerals are
 195 formed and dispersed at their crustal concentration $x_{M_{cr}}$ on the Earth crust, the
 196 specific exergy of the dispersed mineral $ex_M(x_{M_{cr}})$ of the mineral is:

$$ex_M(x_{M_{cr}}) = ex_{chM} \quad (4)$$

197 3. State 2 (Concentrated minerals): The dispersed mineral is concentrated at x_M
 198 into mines, the specific exergy of the concentrated mineral $ex_M(x_M)$ is then:

$$ex_M(x_M) = ex_{chM} + ex_{cM}(x_M) \quad (5)$$

199 Valero's evaluation model (Valero et al., 2002b) is based on hypothetical reversible
 200 conditions, far from real processes where friction and dissipation losses can not be
 201 neglected. The real exergy requirements are, then, much more greater than the ther-
 202 modynamic value which represents only the minimum work that should be invested to
 203 form a given mineral from the reference environment to the conditions in the mine.
 204 In this context, Valero proposes to introduce physical unit costs, k_{chM} and k_{cM} , re-
 205 spectively of the refining and the concentration process of the mineral. This permits
 206 to identify the real exergetic value of minerals, taking into account the limits of the
 207 current available technology, see Equation 6.

$$ex_M^r(x_M) = k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M) \quad (6)$$

208 2.2.2. Exergy decrease of declining non-fuel mineral reserves

209 The exergy of a mineral reserve depends on the grade and size of the ore body. To
 210 evaluate the exergy lost by mineral extraction, the whole life cycle of the reserve should
 211 be considered, from its formation until its depletion. Three main theoretical stages can
 212 be distinguished:

- 213 • *Calculation of the ore deposit's chemical exergy (pre-mine)*, The mineral is dis-
 214 persed at its crustal concentration $x_{M_{cr}}$. The specific exergy of the mineral reserve
 215 $ex_R(x_{M_{cr}})$ is, then, equal to the real specific exergy of the dispersed mineral
 216 $ex_M^r(x_{M_{cr}})$. Its absolute exergy $Ex_R(x_{M_{cr}})$ tends to zero as the mass of extractable
 217 mineral m_M is still negligible:

$$\begin{aligned} ex_R(x_{M_{cr}}) &= ex_M^r(x_{M_{cr}}) = k_{chM} \cdot ex_{chM} \\ Ex_R(x_{M_{cr}}) &\rightarrow 0 \end{aligned} \quad (7)$$

218 It should be noted that only concentrated chemical exergy can be used because
219 it is impossible to extract dispersed minerals with present technology.

220 • *Calculation of the ore deposit's concentration exergy (enrichment)*, The mine is
221 viewed as the result of a natural enrichment process with concentrated minerals.
222 Before extraction, the initial specific exergy of the mineral reserve $ex_R(x_M^\circ)$, is
223 then equal to the real specific exergy of the concentrated mineral $ex_M(x_M^\circ)$. At
224 this stage the stored exergy $Ex_R(x_M^\circ)$ reaches its maximum.

$$\begin{aligned} ex_R(x_M^\circ) &= ex_M^r(x_M^\circ) = k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M^\circ) \\ Ex_R &= m_M^\circ \cdot M_M \cdot ex_R(x_M^\circ) \end{aligned} \quad (8)$$

225 m_M° is the initial total mass of mineral in the mine, M_M is the molar mass of the
226 mineral and x_M° is the initial ore grade of the mine.

227

228 • *Calculation of the ore deposit's exergy decrease (depletion)*, During extraction, the
229 ore grade x_M of the reserve is diminishing ($x_{M_{cr}} \leq x_M \leq x_M^\circ$) and the mineral
230 reserve is losing exergy.

$$\begin{aligned} ex_R(x_M) &= ex_M^r(x_M) = k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M) \\ Ex_R(x_M) &= m_M \cdot M_M \cdot ex_R(x_M) \end{aligned} \quad (9)$$

231 m_M is the remaining mass of mineral in the deposit after extraction and x_M is its
232 corresponding ore grade. It should be stressed that the concentration exergy of the
233 mineral decreases with its ore grade, while the chemical exergy remains constant.
234 When all the mineral is extracted, the mine becomes depleted, the extractable
235 quantity of mineral m_M becomes insignificant, and hence its ore grade x_M tends
236 to the crustal concentration of the mineral $x_{M_{cr}}$. The specific exergy of the reserve
237 ex_R tends then to its specific exergy before enrichment and the stored absolute
238 exergy Ex_R becomes negligible:

$$\lim_{x_M \rightarrow x_{Mcr}} ex_R(x_M) = k_{chM} \cdot ex_{chM} \quad (10)$$

$$\lim_{x_M \rightarrow x_{Mcr}} Ex_R(x_M) = 0$$

239 Figure 3 represents the specific exergy of the mineral reserve at different evolution
 240 stages. It can be seen that the exergy analysis distinguishes two main energy levels, a
 241 degraded one and an enriched one, corresponding respectively to the dispersed and the
 242 concentrated state of the mineral.

243 2.3. *Emergy evaluation model of non-fuel mineral reserves*

244 An emergy evaluation model is proposed that permits to assess the impact of de-
 245 clining non fuel mineral reserves. This method permits to assess on the one hand the
 246 emergy that Nature invested to form mineral deposits and on the other hand the emergy
 247 required to compensate the damages caused by mining.

248 2.3.1. *Emergy decrease of declining non-fuel mineral reserves*

249 In order to evaluate the emergy that would be lost by extracting the mineral from
 250 the mine, the emergy required to create such mineral reserves should be determined.
 251 Three main theoretical evolution processes ought to be taken into account, see Figure 4.

- 252 1. *Earth's crust formation process*: Hazen's mineral evolution theory (Hazen, 2010;
 253 Hazen and Ferry, 2010) and other proposed scenarios of Earth's crust formation
 254 (McCoy, 2010; Valley et al., 2002; Jørgensen et al., 2009; Sverjensky, 2010) illus-
 255 trate the complexity and breath of the processes that participated, over eons, in
 256 developing the mineralogy of the Earth's crust to its present diversification and
 257 distribution. It will be very difficult if not impossible to determine exactly the
 258 energies that drove terrestrial mineral evolution, because little is known about
 259 these processes which are no longer observed in today's world. Nevertheless, dif-
 260 ferent studies had been performed to evaluate the emergy of the Earth's crust.
 261 Based on the work of Garrels et al. (1975), Odum (1996) estimated the specific

262 energy of global sediment to be about $1.62 \text{ E}+9 \text{ seJ/g}$. Brown (2007) calcu-
 263 lated a specific energy of the Earth's crust of about $1.35 \text{ E}+8 \text{ seJ/g}$, assuming
 264 a turnover time of $2.5 \text{ E}+8 \text{ yrs}$ (the values have been converted into the energy
 265 baseline of $1.52 \text{ E}+24 \text{ seJ/yr}$ (Brown and Ulgiati, 2010)). In the next section, a
 266 methodology is proposed to calculate the energy of Earth's crust formation by
 267 using its chemical exergy.

268 Every group of mineral dispersed in the Earth's crust is regarded as individual
 269 component of the latter, characterized by its specific chemical composition and
 270 its abundance, and thus it may be considered, from an energy point of view, as
 271 co-product of the Earth's crust formation process, see Figure 4. This means that
 272 every group of mineral has the same absolute energy as the Earth's crust and
 273 that its specific energy $em_M(x_{M_{cr}})$ is proportional to the specific energy of the
 274 Earth's crust em_{cr} and to its crustal concentration $x_{M_{cr}}$, see Equation 11:

275 **Assumption 1 (*Energy of dispersed minerals*)**

Every group of mineral is assumed to be a co-product of the Earth's crust:
 The absolute energy of any mineral group $Em_M(x_{M_{cr}})$ is equal to the absolute
 energy of the Earth's crust Em_{cr} .

$$Em_M(x_{M_{cr}}) \stackrel{\text{def}}{=} Em_{cr}$$

278 $m_{M_{cr}}$ represents the mass of the mineral in the Earth's crust and m_{cr} represents
 279 the total mass of the Earth's crust. Hence the specific energy of a dispersed
 280 mineral M , $em_M(x_{M_{cr}})$ can be expressed as follows:

$$\begin{aligned} m_{M_{cr}} &= x_{M_{cr}} \cdot m_{cr} \\ em_M(x_{M_{cr}}) &= \frac{Em_{cr}}{m_{M_{cr}}} \\ &= \frac{em_{cr}}{x_{M_{cr}}} \end{aligned} \quad (11)$$

281 Odum (see Citation 2) emphasized that the energy per mass (or specific energy)
 282 of a mineral vary with its abundance in the Earth's crust. The more the mineral

283 is abundant the lower the energy contribution was to create it. The results
 284 of Equation 11 meets exactly what Odum expected (Citation 2 and Citation
 285 3), scarce minerals present higher energy contribution than abundant one. It
 286 should be noted, that $em_M(x_{M_{cr}})$ represents the lowest position of the mineral in
 287 the material hierarchy, because the mineral cannot be dissipated spontaneously
 288 further than its crustal concentration $x_{M_{cr}}$.

289 **Citation 6 (*An energy hierarchy law for biochemical cycles*)**

«... any increase in concentration of material requires an increase
 in the energy per mass. When concentration increase in some
 part of a biogeochemical cycle, the energy per mass increases.»
 (Odum (2000a))

292 2. *Concentration of minerals into ore deposits*: Odum (Citation 6) stressed that com-
 293 pared to its dispersed state (at crustal concentration $x_{M_{cr}}$), concentrated minerals
 294 required more work to be formed and thus, the more the mineral is concentrated
 295 the more available energy had been degraded and the higher the energy per mass
 296 will be (i.e. the higher its position in the material hierarchy). Actually, the qual-
 297 ity of a mineral reserve depends on the quantity m_M° and on the concentration
 298 of the stored mineral x_M° . In this work, it is considered that the same sources
 299 of energy (τ_F is the average transformity of these sources) that created dispersed
 300 minerals, concentrated further a part of them into mines, see Figure 4. Thus,
 301 the specific energy of the mineral reserve em_R can be calculated by using the
 302 mineral's exergy, the specific energy of the dispersed mineral $em_M(x_{M_{cr}})$ and the
 303 ore grade of the deposit x_M° .

304 **Assumption 2 (*Emergy of mineral reserves*)**

The sources of energy that created dispersed minerals in the Earth's crust are

305

expected to be the same source that concentrated a part of them into mineral reserves.

$$\tau_F \stackrel{\text{def}}{=} \frac{Em_M(x_{M_{cr}})}{Ex_M(x_{M_{cr}})} \stackrel{\text{def}}{=} \frac{Em_R(x_M^\circ)}{Ex_R(x_M^\circ)} \quad (12)$$

306

308 The initial specific energy $em_R(x_M^\circ)$ of an ore reserve of mineral M with an ore
309 grade x_M° can be calculated, then, by using Equation 13 :

$$\begin{aligned} em_R(x_M^\circ) &= em_M(x_{M_{cr}}) \cdot \frac{ex_R(x_M^\circ)}{ex_M(x_{M_{cr}})} \\ &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[\frac{k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M^\circ)}{k_{chM} \cdot ex_{chM}} \right] \\ &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[1 + \frac{k_{cM} \cdot ex_{cM}(x_M^\circ)}{k_{chM} \cdot ex_{chM}} \right] \end{aligned} \quad (13)$$

310

311 The total amount of energy $Em_R(x_M^\circ)$ stored initially in the mine can be ex-
312 pressed as follows:

$$Em_R(x_M^\circ) = m_M^\circ \cdot em_R(x_M^\circ) \quad (14)$$

313 It should be underlined that $em_R(x_M^\circ)$ and $Em_R(x_M^\circ)$ are the highest values the
314 mine can ever reach during its life cycle.

315 It can be noted that the results of Equation 13 are consistent with the material
316 hierarchy. The specific energy of the mineral reserve increases with its ore grade
317 x_M° and conversely when its ore content decline to its lowest value ($x_{M_{cr}}$), the
318 specific energy of the deposit tends to its lowest level in the material's hierarchy,
319 which corresponds to the crustal specific energy of the mineral:

$$\lim_{x_M^\circ \rightarrow x_{M_{cr}}} em_R = em_M(x_{M_{cr}})$$

320 Besides, when the abundance of the mineral $x_{M_{cr}}$ tends to 1 (which means that
 321 the whole Earth's crust is composed of mineral M), the specific energy of the
 322 mineral reserve tends to the specific energy of the Earth's crust:

$$\lim_{x_{M_{cr}} \rightarrow 1} em_R = em_{cr}$$

323 In order that Equation 1 proposed by (Cohen et al., 2007) and (Brown, 2007) will
 324 be coherent with the material hierarchy concept, the enrichment factor is expected
 325 to express the real work that Nature had invested to concentrate the mineral
 326 and the baseline should be the minimum specific energy the mineral could reach
 327 naturally when it is dispersed. Therefore, to enhance this methodology the results
 328 of Equation 13 may be used. Instead of an universal baseline B_R for any mineral
 329 reserve, the crustal specific energy of the corresponding mineral $em_M(x_{M_{cr}})$ is
 330 proposed, since its most natural degraded state is when it is dispersed. The
 331 enrichment factor ER_R can be defined as the ratio between the specific exergy of
 332 the concentrated ore reserve $ex_R(x_M^\circ)$ and the crustal specific exergy of the mineral
 333 $ex_M(x_{M_{cr}})$. This permits to integrate the effort invested by Nature to upgrade
 334 the mineral from its dispersed state to its concentrated state in the mine.

335 **Proposition 1 (*Baseline and enrichment factor of mineral reserves*)**

The baseline is assumed to be the crustal specific energy of the mineral:

$$B_R(x_{M_{cr}}) \stackrel{def}{=} em_M(x_{M_{cr}}) \quad (15)$$

The enrichment factor is defined as the ratio between the specific exergy of the concentrated ore reserve $ex_R(x_M^\circ)$ and the crustal specific exergy of the mineral $ex_M(x_{M_{cr}})$:

$$EF_R(x_M^\circ) \stackrel{def}{=} \frac{ex_R(x_M^\circ)}{ex_M(x_{M_{cr}})} \quad (16)$$

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It should be underlined that for an appropriate energy evaluation, first the sources and pathways should be identified. Thus, it seems unreal to equate, as done in Equation 1, the specific energy of mineral reserves without considering their formation process. Therefore, Proposition 1 was made after defining a theoretical evolution process of mineral reserves, illustrated in Figure 4. The results reflects, then, the pathway of mineral reserve formation as the specific energy of the reserve depends on the chemical properties and abundance of the mineral and the initial conditions of the reserve, see Equation 13.

347

Citation 7 (An energy hierarchy law for biochemical cycles)

348

« When material disperses, the stored energy decreases. » (Odum (2000a))

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355

3. *Extraction of the mineral from the mine:* Owing to its chemical and concentration potential, a mineral reserve can be considered as an energy reservoir furnished by Nature to meet human needs. With the extracted mineral the mine loses chemical and concentration potential, the mineral content m_M and grade x_M of the ore body diminishes ($m_M < m_M^\circ$; $x_M < x_M^\circ$) which leads to a reduction of its stored energy. It is expected that, during the mining, not only the total

356 energy of the ore body Em_R diminishes but also its specific energy em_R , as its
 357 concentration potential decreases with its ore grade. Complying with the energy
 358 hierarchy concept, see Citation 7 this means that during extraction, the mine loses
 359 its available energy (in form of chemical and concentration exergy) and descend,
 360 then, to a lower level in the energy hierarchy.

361 The present study is not concerned with assessing the work required to extract
 362 the mineral from the mine but instead with estimating the emergy that would be
 363 definitely lost due to mineral exploitation. Therefore, in order to calculate the
 364 variation of the specific emergy of the ore deposit with mining, the extraction of
 365 the mineral can be simulated by a natural dilution of the ore body generated by
 366 the same sources of energy that concentrated it before, see Figure 4. This means
 367 that the ore body of the reserve will be diluted from its initial ore grade x_M° to a
 368 lower concentration x_M after mining.

369 **Assumption 3 (*Emergy decrease of declining mineral reserves*)**

The extraction of the mineral from the mine can be assimilated to a natural dilution of the ore body from its initial ore grade x_M° to a lower concentration x_M , generated by the same sources of energy that previously concentrated the mineral into the mine.

$$\tau_F \stackrel{def}{=} \frac{Em_R(x_M^\circ)}{Ex_R(x_M^\circ)} \stackrel{def}{=} \frac{Em_R(x_M)}{Ex_R(x_M)} \quad (17)$$

370

372 Thus the specific emergy of the declining ore reserve $em_R(x_M)$ can be expressed
 373 as follows :

$$em_R(x_M) = em_R(x_M^\circ) \cdot \frac{ex_R(x_M)}{ex_R(x_M^\circ)}$$

According to Equation 13:

$$\begin{aligned} em_R(x_M) &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[\frac{k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M)}{k_{chM} \cdot ex_{chM}} \right] \\ &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[1 + \frac{k_{cM} \cdot ex_{cM}(x_M)}{k_{chM} \cdot ex_{chM}} \right] \end{aligned} \quad (18)$$

374

375 The remaining stored emergy after mining $Em_R(x_M)$ with an ore grade x_M con-
376 taining a quantity m_M of extractable mineral, is then:

$$Em_R(x_M) = m_M \cdot em_R(x_M) \quad (19)$$

377

378

379

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382

Once the ore reserve has been exhausted, its ore grade and specific emergy approaches respectively the crustal concentration $x_{M_{cr}}$ and the crustal specific emergy of the mineral $em_R(x_{M_{cr}})$. Theoretically, the consumed reserve is at the lowest position in the material hierarchy that it can ever attain naturally. The stored emergy of the reserve tends to zero. The chemical potential of the mineral in the mine is no longer exploitable.

$$\begin{aligned} \lim_{x_M \rightarrow x_{M_{cr}}} em_R(x_M) &= em_M(x_{M_{cr}}) \\ \lim_{x_M \rightarrow x_{M_{cr}}} Em_R(x_M) &= 0 \end{aligned} \quad (20)$$

383

384

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388

Analogous to Equation 1, the specific emergy of a declining mineral reserve $em_R(x_M)$ may be expressed, as a function of its baseline B_R and its depletion factor DF_R . To be in conformity with the material hierarchy, the baseline should represent the highest specific emergy of the mine during its life cycle, and the depletion factor is expected to quantify the concentration ability of the mine at any stage of degradation. According to Equation 18, $em_R(x_M^\circ)$ can be defined as

389 the baseline of the reserve, the ratio between the specific exergy of the ore body
 390 after mining $ex_R(x_M)$ and the initial specific exergy of the mine $ex_R(x_M^\circ)$ can be
 391 considered as the depletion factor of the reserve.

392 **Proposition 2 (*Baseline and depletion factor of declining mineral reserves*)**

The initial specific emergy of the mineral is proposed as baseline:

$$B_R(x_M^\circ) \stackrel{def}{=} em_R(x_M^\circ) \quad (21)$$

The depletion factor is defined as the ratio between the specific exergy of the
 ore body after mining $ex_R(x_M)$ and the initial specific exergy of the mine
 $ex_R(x_M^\circ)$:

$$DF_R(x_M) \stackrel{def}{=} \frac{ex_R(x_M)}{ex_R(x_M^\circ)} \quad (22)$$

393

395 *2.3.2. Emergy evaluation of land degradation due to mining*

396 A mine can be considered as a part of the Earth's crust containing high concentrated
 397 mineral ores. The extraction of these ores not only causes the loss of mine's chemical
 398 and concentration potential but also the devastation of the landscape. Contrarily to
 399 the previous section where only the depletion of the mineral reserve has been studied,
 400 the present section deals with the degradation of the whole mine due to its exploitation
 401 and the efforts that should be applied to remedy the mining impacts.

402 The concentrated mineral content of the mine differentiates it from its environment.
 403 It can be assumed, then, that the total emergy of the mine Em_{Mine} is equal to the total
 404 emergy of its mineral reserve Em_R .

405 **Assumption 4 (*Emergy of mines*)**

The total emergy of the whole mine Em_{Mine} is equal to the total emergy of

406

its mineral reserve Em_R :

$$Em_{Mine}(x_M) = Em_R(x_M) \quad (23)$$

$$m_M = x_M \cdot m_{Mine}$$

408

409 According to Equation 18 the specific energy of the mine em_{Mine} can be expressed
410 as follows:

$$em_{Mine} = x_M \cdot em_R(x_M) \quad (24)$$

$$em_{Mine}(x_M) = em_{cr} \cdot \frac{x_M}{x_{M_{cr}}} \cdot \left[1 + \frac{k_c \cdot ex_c(x_M)}{k_{ch} \cdot ex_{ch}} \right]$$

411 When the mine is completely exhausted its ore grade tends to the crustal concentra-
412 tion of the mineral $x_{M_{cr}}$ and the stored energy in form of mineral reserves approaches
413 zero because the quantity of extractable mineral becomes negligible. Based on Equa-
414 tion 24 the specific energy of the depleted mine tends to the specific energy of the
415 Earth's crust em_{cr} :

$$\lim_{x_M \rightarrow x_{M_{cr}}} em_{Mine}(x_M) = em_{cr} \quad (25)$$

416

417 This shows that the depleted mine lost all its specific potentials that differentiate it
418 from the rest of the surrounding land (where the average specific energy is em_{cr}). In
419 terms of material hierarchy, this means that the mine is at the lowest position that it
420 can ever reach in the hierarchy. Besides, during mining, the Earth in the mine has been
421 removed to obtain the mineral. Hence, the total energy of the empty mine tends to
422 zero, and the post-mining ecosystem is out of balance because a part of the Earth's crust
423 is missing. Additional work is required to restore the devastated land. It is possible
424 to bulldoze the earth into the mine, but Odum specified (see Citation 8) that natural
425 restored post-mining land is more valuable than artificially recovered land. Thus, the

426 theoretical total emergy that Nature should invest to restore for itself the balance of
 427 the ecosystem Em_{Rest} can be calculated by multiplying the removed mass of the mine
 428 m_{rem} with the specific emergy of the Earth's crust em_{cr} .

$$Em_{Rest} = m_{rem} \cdot em_{cr} \quad (26)$$

429 It should be outlined that Em_{Rest} represents the theoretically minimum work that
 430 should be done to reestablish the post-mining land, because after restoration the former
 431 mine becomes an ordinary part of the Earth's crust without any particularly chemical
 432 or concentration potential, as the mined mineral has been replaced by ordinary earth.
 433 Besides pollution and other impacts of mining are not taken into account.

434 **Citation 8 (*Environmental accounting*)**

«Kangas (1983), evaluating the emergy of landforms and their
 colonization by ecosystems, found that irregular, post-mining lands,
 which had 20-40 yr of natural restoration through ecological suc-
 cession and other processes, were more valuable than those lands
 that were bulldozed flat in well-intentioned restoration.» (Odum
 (1996), p.123)

435
 437 Figure 5 represents the life cycle of the mine, taking into account the restoration
 438 process after mining. It can be seen that this evaluation model distinguish three phases:
 439 a degraded, an enriched and a destroyed one where natural additional work is required
 440 for restoration. This shows that contrarily to the exergy analysis (see Figure 2) this
 441 emergy approach permits to evaluate the impact of mining and the work that should
 442 be done to restore the post-mining ecosystem.

443 3. Results

444 3.1. Proposition of Earth's crust emergy calculation

445 The evolution and diversification of terrestrial minerals is a consequence of all the
446 physical, chemical and biochemical processes through which the Earth has passed since
447 its creation four and a half billion years ago. The degree of mineral complexity of the
448 planet is a result of local, regional and global selective processes enforced by Nature.
449 The diversity and distribution of its terrestrial minerals reflect the intensity of the cyclic
450 processes that have affected the Earth during its formation. Thus, to evaluate the
451 emergy of the Earth's crust the historical context of mineral genesis should be studied.
452 Or, it seems to be almost impossible to evaluate the energies involved in the Earth's
453 crust formation with today's emergy scale because the Earth, at this time, was exposed
454 to large sources of energy much more greater than present work of the geobiosphere.
455 Indeed, the internal and external sources of heat were considerably more important
456 (the radioactive heat generation was about five times higher than today (Valley et al.,
457 2002)). Besides, the planet was subjected to heavy meteorite bombardments (Jørgensen
458 et al., 2009) and extreme climate change (Hazen, 2010).

459 Recent studies had been performed to calculate the chemical exergy of the conti-
460 nental crust (Valero et al., 2012), the results may be used to determine the emergy of
461 Earth's crust formation by using the appropriate transformity. Valero et al. (2011) em-
462 phasized that the abundance of concentrated chemical exergy is negligible compared to
463 the whole Earth's crust since concentrated mineral resources (fuel and non-fuel origin)
464 only represent 0.001% of the Earth's upper crust mass. And as their concentration ex-
465 ergies ex_c (without adding unit exergy costs) are much more lower than their chemical
466 exergies ex_{ch} (Valero, 2008), the concentration potential of the Earth's crust can be
467 neglected compared to its chemical potential, and its total exergy can be assimilated
468 to its chemical exergy. Valero et al. (2012) proposed a thermodynamic evaluation tool
469 which permits to calculate the chemical exergy wealth of the Earth's crust based on a
470 framed model of the crust in its dispersed state, comprising about 300 of the most abun-

471 dant minerals. The study is based on the crepuscular crust model developed previously
 472 by (Valero et al., 2011) to determine the chemical composition of the upper continen-
 473 tal crust and on Szargut's Reference Evaluation Methodology (Szargut et al., 2005) to
 474 calculate the chemical exergy of any substance in the upper crust. The **molar** chemical
 475 exergy of the Earth's upper crust is estimated to be about $ex_{cr} = 3.63 \text{ E}+3 \text{ J/mol}$
 476 which indicates an absolute chemical exergy of $Ex_{cr} = 2.53 \text{ E}+26 \text{ J}$, for a molar weight
 477 of $M_{cr} = 155.2 \text{ g/mol}$. The results are manifestly very rough and need further updates,
 478 but they inform well enough about the order of magnitude of the chemical wealth of
 479 the Earth crust.

480 To calculate the emergy of the Earth's crust Em_{cr} basing on Valero's exergy analysis,
 481 the adequate transformity should be identified. Or, it is very difficult at this state
 482 of knowledge to evaluate precisely where the energies, involved in the Earth's crust
 483 evolution, are placed in the universal energy hierarchy. The emergy approach consider
 484 that sunlight, tidal energy and geothermal heat are the three main sources of energy
 485 that drove the complex processes of the geobiosphere and that these sources contributed
 486 to the Earth crust formation (Odum, 1996). Thus, the emergy Em_{cr} can be expressed
 487 as follows:

$$Em_{cr} = \alpha \cdot Em_{geobio} \cdot t \quad (27)$$

488 Where Em_{geobio} is the annual emergy of the geobiosphere, α is the part of this
 489 emergy that generated the Earth crust formation and t is the turnover time. In terms
 490 of exergy Em_{cr} is then:

$$Em_{cr} = \tau_{geobio} \cdot \alpha \cdot Ex_{geobio} \cdot t \quad (28)$$

491 Where Ex_{geobio} is the annual exergy of the geobiosphere and τ_{geobio} is the average
 492 transformity of the geobiosphere. Hence, to calculate Em_{cr} the values of α and t should
 493 be determined as Ex_{geobio} and τ_{geobio} are known. Brown (2007), for example, considered

494 that the entire annual exergy of the geobiosphere drove the Earth crust formation (i.e.
495 $\alpha = 1$) and that the turnover time was about $2.5 \text{ E}+8$ yrs.

496 Basing on this, it can be assumed that the term " $\alpha \cdot Ex_{geobio} \cdot t$ " reflects the pathway
497 of the Earth crust formation and that the exergy of the Earth crust Ex_{cr} calculated by
498 Valero et al. (2012) represents the result of this formation process:

$$\alpha \cdot Ex_{geobio} \cdot t \approx Ex_{cr} \quad (29)$$

499 And thus, according to Equation 28 Em_{cr} can be expressed as follows:

$$Em_{cr} = \tau_{geobio} \cdot Ex_{cr} \quad (30)$$

500 For the numerical application the average transformity of the geobiosphere calcu-
501 lated by Brown and Ulgiati (2010) is used. Nevertheless, it should be underlined that
502 the proposed evaluation method remains valid what ever value of Em_{cr} or τ_F is chosen.

503 **Proposition 3 (Transformity of the Earth's crust)**

The transformity of Earth's crust formation τ_F is assumed to be equal to the
average transformity of the geobiosphere τ_{geobio} .

$$\tau_F \stackrel{def}{=} \tau_{geobio} = 4.2 \text{ seJ/J}$$

506 The emergy of the Earth's crust is obtained, then, by multiplying its exergy by the
507 transformity, which gives an emergy of about $Em_{cr} = 1.06 \text{ E}+27 \text{ seJ}$, see Table 1.

$$Em_{cr} \stackrel{def}{=} \tau_F \cdot Ex_{cr} \quad (31)$$

508 3.2. Application to the main commercially used minerals

509 Dispersed minerals are considered as co-products of the Earth's crust, thus absolute
510 emergy of the dispersed mineral is equal to the absolute emergy of the Earth's crust.
511 In this work, 42 of the main commercially used minerals has been studied. Table 2

512 summarizes the chemical properties of these minerals (Valero et al., 2009). Table 3
 513 displays the specific energy of dispersed minerals, calculated by Equation 11. It can be
 514 seen that the results are consistent with the material's hierarchy, as scarce minerals like
 515 gold or silver have higher crustal specific energies than abundant minerals like iron or
 516 nickel. In Table 4 the specific energy of mineral reserves are calculated based on differ-
 517 ent approaches. The specific energy em_R^1 and em_R^2 are both based on Equation 1, the
 518 first used a baseline of 1.62 E+9 seJ/g proposed by Cohen et al. (2007) and the second
 519 a baseline of 1.35 E+8 seJ/g updated by Brown (2007). The last column represents the
 520 specific energy of mineral reserves calculated by the method proposed in the current
 521 work (see Equation 18), using the ore grade cutoff of the mine (*OGC*, see Table 4). It
 522 can be noted that the order of magnitude of em_R is mostly closer, to Brown's results
 523 em_R^2 who used the specific energy of the Earth's crust as baseline. Nevertheless, sig-
 524 nificant divergence for some minerals can be observed such as gold, tantalum or zinc.
 525 This can be explained by the fact that Brown (2007) used, similarly to this work, the
 526 average transformity of the geobiosphere τ_{geobio} to calculate the specific energy of the
 527 Earth crust, see proposition 3. But choosing the latter as universal baseline for all
 528 minerals is not sufficient because this is not consistent with the material hierarchy and
 529 does not include the chemical potential of the mineral.

530 3.3. Application to the energy decrease of mineral reserves: Case of some Australian 531 mineral reserves

532 Since the late 18th century several mining booms occurred in Australia. In this
 533 section the energy decrease of some Australian mineral reserves such as gold, copper,
 534 nickel, silver, lead, zinc and iron has been studied, the required data has been taken
 535 from Valero (2008). Table 5 represents the main characteristics of these reserves since
 536 their discovery until now. The initial specific energies $em_R(x_M^\circ)$ and the current specific
 537 energy $em_R(x_M)$ have been calculated by using Equation 18 and respectively the initial
 538 and current ore grades x_M° and x_M , listed in Table 5. The last column of this table
 539 represents, in percent, the specific energy decrease of mineral reserves D . The results

540 reveal that, over the past century, especially gold, copper and lead reserves suffered
 541 from a drastic decrease by about 30% in specific emergy, due to the fact that their
 542 ore grades have notably declined. Whereas, in spite of the huge quantities of iron that
 543 are mined every year the ore grade of iron reserve little changed due to the abundance
 544 of iron rich deposits in Australia and thus the specific emergy of iron reserve remains
 545 almost constant.

546 3.4. Application to the land degradation of ore deposits: Case of US copper mines

547 The aim of this section is to evaluate the emergy loss of US copper deposits when
 548 all their reserves are exhausted and to estimate the minimum emergy that Nature
 549 should invest to replace the extracted mineral from the mines. In order to use the
 550 methodology proposed in Equation 24 and Equation 26, it is assumed that US copper
 551 reserves represent a huge mine with an initial ore grade x_{Copper}° and an initial mineral
 552 content m_{Copper}° . Because of data unavailability, the mining activity before the year
 553 1900 has been neglected. The initial copper mass m_{Copper}° has been determined by
 554 cumulating the primary copper production from 1900 to 2001, adding them the reserve
 555 base of the year 2001 (USGS, 2011). This permits to obtain an ore mass of about
 556 $m_{Copper}^{\circ} = 1.84E+11$ kg, the initial ore grade of copper in 1900 was about 2% (Valero,
 557 2008). The calculation reveals that the emergy $Em_{Mine}(x_{Copper}^{\circ})$ lost irreversibly by the
 558 ecosystem when all the mineral is extracted is about $7.26 E+20$ seJ and that the emergy
 559 Em_{Rest} required to replace the mined mineral by ordinary earth is about $1.81E+16$ seJ
 560 (it is considered that only the mineral reserve would be removed from the mine i.e.
 561 $m_{rem} = m_{Copper}^{\circ}$). The results are summarized in Table 6.

562 4. Conclusion

- 563 1. Emergy and exergy assessment tools have been combined to evaluate the envi-
 564 ronmental impact of mining, considering only the natural exergy of the mineral.
- 565 2. Every group of dispersed mineral is assumed to be a co-product of the Earth's
 566 crust. The specific emergy of about 40 main commercially used minerals have

567 been calculated, respecting the material hierarchy as the specific energy rise with
568 scarcity.

569 3. An evaluation model was proposed that permits to calculate the specific energy
570 of mineral reserves based on the chemical and concentration exergy of the mineral,
571 its abundance and concentration in the mine. The application to some Australian
572 mineral reserves shows that the specific energy of the reserve decreases with its
573 ore grade. Theoretically, when all the reserve is exhausted its specific energy
574 tends to the crustal specific energy of the mineral $em_M(x_{M_{cr}})$, representing the
575 lowest position that the reserve can ever reach in the material hierarchy.

576 4. To make the methodology realized by Cohen et al. (2007) and Brown (2007) con-
577 sistent with the material hierarchy, it is proposed to use instead of an universal
578 baseline the crustal specific energy of the mineral $em_M(x_{M_{cr}})$ and as enrich-
579 ment factor the ratio between the specific exergy of the concentrated ore reserve
580 $ex_M(x_M^\circ)$ and the crustal specific exergy of the mineral $ex_M(x_{M_{cr}})$ (see Proposition
581 1).

582 5. To assess the impact of mining on the ecosystem, a methodology is introduced
583 that permits to quantify the theoretical minimum energy that Nature should
584 invest to restore the post-mining land. The application to the US copper mines
585 reveals that the ecosystem will loose about $7.26 \text{ E}+20 \text{ seJ}$ when all the copper
586 reserves have been extracted and that Nature should invest at least about 1.81
587 $\text{E}+16 \text{ seJ}$ to restore the post-mining land.

588 6. Although different methods could be envisaged to calculate the energy of the
589 Earth's crust, the proposed evaluation model remains valid whatever numerical
590 value of the latter is chosen

591 **5. Appendix**

592 The energy approach consider that sunlight, tidal energy and geothermal heat
593 are the three main sources of exergy that drive the complex processes of the geobio-
594 sphere Odum (1996). The annual global energy budget is calculated by multiplying
595 the annual exergy flows of these sources by their transformities, as shown in Table 7.
596 Admitting that the transformity of solar is equal to one, the transformities of tidal
597 and geothermal heat has been calculated by establishing two equations: one expressing
598 the exergy contributions to geothermal heat and the other the exergy contributions to
599 ocean geopotential. The average transformity of the geobiosphere τ_{geobio} is then the
600 ratio between the annual energy flow of the geobiosphere Em_{geobio} and its exergy flow
601 Ex_{geobio} , see Equation 32. All the unit energy values used in this work are based on
602 the annual energy budget of the geobiosphere calculated by Brown and Ulgiati (2010),
603 see Table 7.

$$\tau_{geobio} = \frac{Em_{geobio}}{Ex_{geobio}} \quad (32)$$

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621 **Nomenclature**622 **Acronyms**623 *OGC* Ore grade cutoff [-]624 **Greek Symbols**625 λ Ratio between the molar mass of mineral M_M and the average molar mass of
626 the mixture M_{tot} , $\lambda_M = \frac{M_{tot}}{M_M}$ [-]627 α Part of the emergy of the geobiosphere that contributed to the Earth crust
628 formation629 τ Transformity630 **Roman Symbols**631 *B* Baseline [seJ/g]632 Δg_f Specific Gibbs free energy of mineral formation [J/g]633 *ER* Enrichment factor, $ER = \frac{OGC}{x_{Mcr}}$ [-]634 *Em* Absolute emergy [seJ]635 *em* Specific emergy [seJ/g]636 *Ex* Absolute exergy [J]637 *ex* Specific exergy [J/mol]638 *k* Unit exergy replacement cost [-]639 *M* Molar mass [g/mol]640 *m* mass [g]641 *R* Universal gas constant [8.314 J/mol K]

642 T° Standard ambient temperature [298.15 K]

643 x Massic fraction [g/g]

644 y Molar fraction [mol/mol]

645 **Superscripts**

646 $^\circ$ Initial conditions

647 r Real exergy cost

648 **Subscripts**

649 c Concentration

650 ch Chemical

651 cr Crust

652 F Earth crust formation

653 $geobio$ Geobiosphere

654 i Component i

655 M Mineral

656 $Mine$ Mine

657 R Mineral reserve

658 rem Removed

659 $Rest$ Restoration

660 **References**

- 661 Brown, M.T., 2007. Material Cycles and Energy Hierarchy. Online un-
662 der:<http://www.cep.ees.ufl.edu/emergy/resources/presentations.shtml>, 2013.
- 663 Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: H.T. Odum's
664 contributions to quantifying and understanding systems. *Ecological Modelling* 178,
665 201–213.
- 666 Brown, M.T., Ulgiati, S., 2010. Updated evaluation of exergy and emergy driving the
667 geobiosphere: A review and refinement of the emergy baseline. *Ecological Modelling*
668 221, 2501–2508.
- 669 Burnett, M.S., 1981. A methodology for assessing net energy and abundance of energy
670 resources. *Energy and Ecological Modelling* , 703–710.
- 671 Cohen, M.J., Sweeny, S., Brown, M.T., 2007. Computing the
672 Unit Emergy Value of Crustal elements, in: *Proceedings of the*
673 *fourth Biennial Emergy*, Center for Environmental Policy, Univer-
674 sity of Florida, Gainesville, Florida. pp. 16.1–16.12. Online under:
675 http://www.cep.ees.ufl.edu/emergy/conferences/ERC04_2006/proceedings.shtml.
- 676 Garrels, R.M., Mackenzie, F.T., Hunt, C., 1975. *Chemical cycles and the Global Envi-*
677 *ronment*. Wiliam Kaufmann, Los Altos, California.
- 678 Hazen, R., 2010. The evolution of minerals. *Scientific American* 303, 58–65.
- 679 Hazen, R., Ferry, J., 2010. Mineral evolution: Mineralogy in the fourth dimension.
680 *Elements* 6, 9–12.
- 681 Jorgensen, S., 2006. *Eco-Exergy as Sustainability*. WIT Press, UK.
- 682 Jørgensen, U.G., Appel, P.W.U., Hatsukawa, Y., Frei, R., Oshima, M., Toh, Y., Kimura,
683 A., 2009. The Earth-Moon system during the late heavy bombardement period -
684 Geochemical support for impacts dominated by comets. *Icarus* 204, 368–380.

- 685 Martinez, A., Valero, A., Valero-Delgado, A., Arauzo, I., 2007. Comparing the
686 Earth's Mineral Wealth from the Point of View of Emergy and Exergetic Cost
687 Analysis, in: Proceedings of the fourth Biennial Emergy, Center for Environmen-
688 tal Policy, University of Florida, Gainesville, Florida. pp. 17.1–17.14. Online under:
689 http://www.cep.ees.ufl.edu/emergy/conferences/ERC04_2006/proceedings.shtml.
- 690 McCoy, T.J., 2010. Minerological evolution of meteorites. *Elements* 6, 19–23.
- 691 Odum, H.T., 1996. *Environmental Accounting: Emergy and Environmental Decision*
692 *Making*. John Wiley & Sons, New York.
- 693 Odum, H.T., 2000a. An Energy Hierarchy Law For Biogeochemical Cycles,
694 in: Proceedings of the first Biennial Emergy, Center for Environmental Pol-
695 icy, University of Florida, Gainesville, Florida. pp. 235–248. Online under:
696 http://www.cep.ees.ufl.edu/emergy/conferences/ERC01_1999/proceedings.shtml.
- 697 Odum, H.T., 2000b. Handbook of Emergy Evaluation Folio 2: Emergy of Global
698 Processes. Center for Environmental Policy, University of Florida. Online under:
699 http://www.cep.ees.ufl.edu/emergy/documents/folios/Folio_02.pdf.
- 700 Riekert, L., 1974. The efficiency of energy utilization in chemical processes. *Chem.*
701 *Eng. Sci* 29, 1613–1620.
- 702 Sciubba, E., 2010. On the Second-Law inconsistency of emergy analysis. *Energy* 1, 11.
- 703 Sverjensky, D.A., 2010. The Great Oxydation Event and mineral diversification. *Ele-*
704 *ments* 6, 31–36.
- 705 Szargut, J., 1989. Chemical exergies of the elements. *Applied Energy* 32, 269–286.
- 706 Szargut, J., Valero, A., Stanek, W., D, A.V., 2005. Towards an international legal
707 reference environment, in: Proceedings of ECOS 2005, Trondheim, Norway. pp. 409–
708 420.

- 709 Szargut, J., Ziebig, A., Stanek, W., 2002. Depletion of the non-renewable natural exergy
710 resources as a measure of the ecological cost. *Energy Conversion and Management* ,
711 1149–1163.
- 712 USGS, 2011. Historical statistics for mineral and material commodities
713 in the United States. Report. US Geological Survey. Online under:
714 <http://minerals.usgs.gov/ds/2005/140/>.
- 715 Valero, A., 1998. Thermoeconomics as a conceptual basis for energy-ecological analysis,
716 in: Ulgiati, S. (Ed.), *Advances in Energy Studies. Energy Flows in Ecology and*
717 *Economy*, Musis, Roma. pp. 415–444.
- 718 Valero, A., 2008. Exergy evolution of the mineral capital on earth. Ph.D. thesis.
719 University of Zaragoza. Zaragoza, Spain.
- 720 Valero, A., Botero, E., Valero, A., 2009. Global Exergy Accounting of Natural Re-
721 sources, in: *EOLLS Encyclopedia of life support systems* (Ed.), *Exergy, Energy Sys-*
722 *tem Analysis and Optimization*, pp. 409–420.
- 723 Valero, A., Ranz, L., Botero, E., 2002a. Exergetic Evaluation of Natural Mineral Capital
724 (1) Reference Environment Methodology, in: Tsatsaronis, G., Moran, M., Cziesla, F.,
725 Bruckner, T. (Eds.), *ECOS 2002*, Berlin. pp. 54–61.
- 726 Valero, A., Ranz, L., Botero, E., 2002b. Exergetic evaluation of Natural Mineral Capital
727 (2). Application of the methodology to current world reserves., in: Tsatsaronis, G.,
728 Moran, M., Cziesla, F., Bruckner, T. (Eds.), *ECOS 2002*, Berlin. pp. 62–68.
- 729 Valero, A., Valero, A., 2005. The crepuscular planet. part ii: A model for the exhausted
730 continental crust, in: *Proceedings of ECOS 2005*, Trondheim, Norway. pp. 409–420.
- 731 Valero, A., Valero, A., Arauzo, I., 2008. Evolution of the decrease in mineral exergy
732 throughout the 20th century. the case of copper in the us. *Energy* 33, 107–115.

- 733 Valero, A., Valero, A., Gómez, J.B., 2011. The crepuscular planet. A model for the
734 exhausted continental crust. *Energy* 36(1), 694–707.
- 735 Valero, A., Valero, A., Veillard, P., 2012. The thermodynamic properties of the upper
736 continental crust: Exergy, Gibbs free energy and enthalpy. *Energy* 41, 121–127.
- 737 Valley, J.W., Peck, W.H., King, E.M., Wilde, S.A., 2002. A cool early Earth. *Geology*
738 4, 351–354.

Figure1

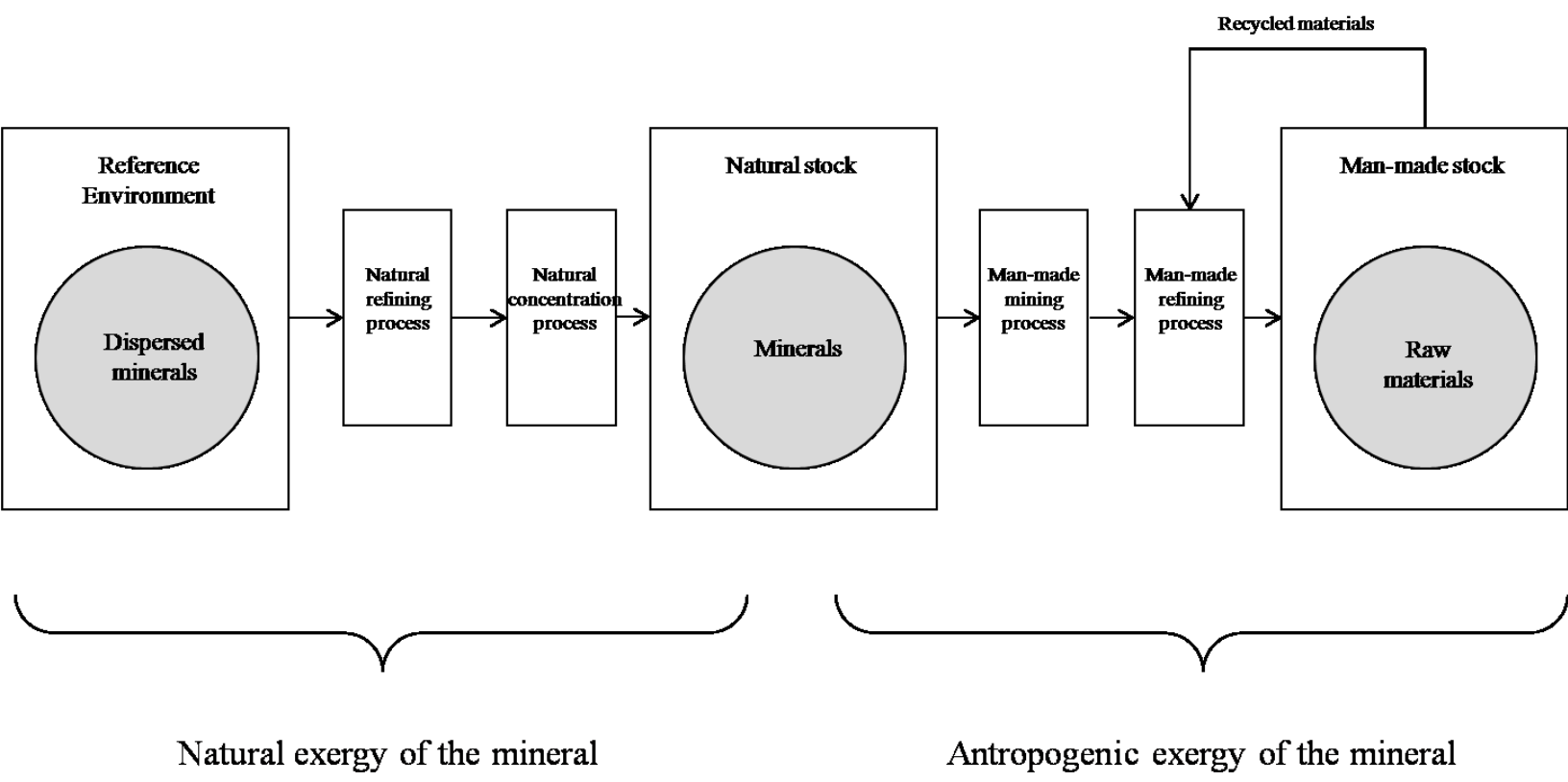
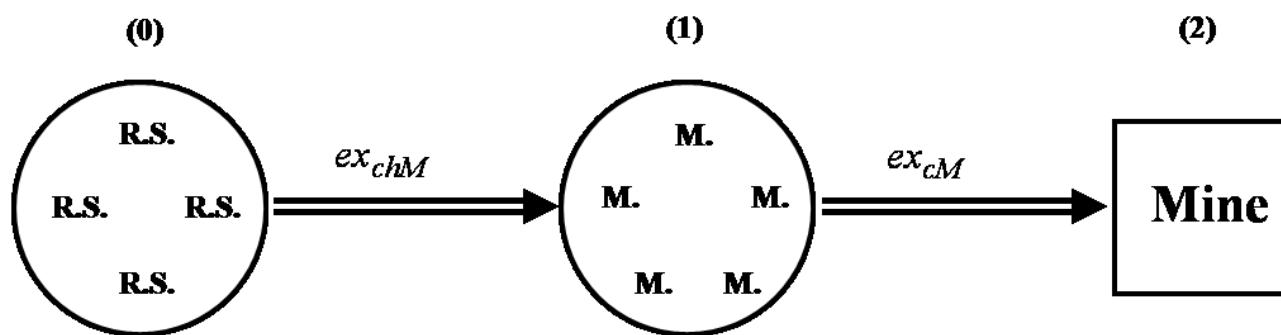


Figure2



State 0: Dispersed Reference substances in the degraded Earth

State 1: Dispersed mineral in the Earth crust at $x_{M_{cr}}$

State 2: Concentrated mineral in the mine at x_M

R.S.: Reference substances
M.: Minerals

Figure3

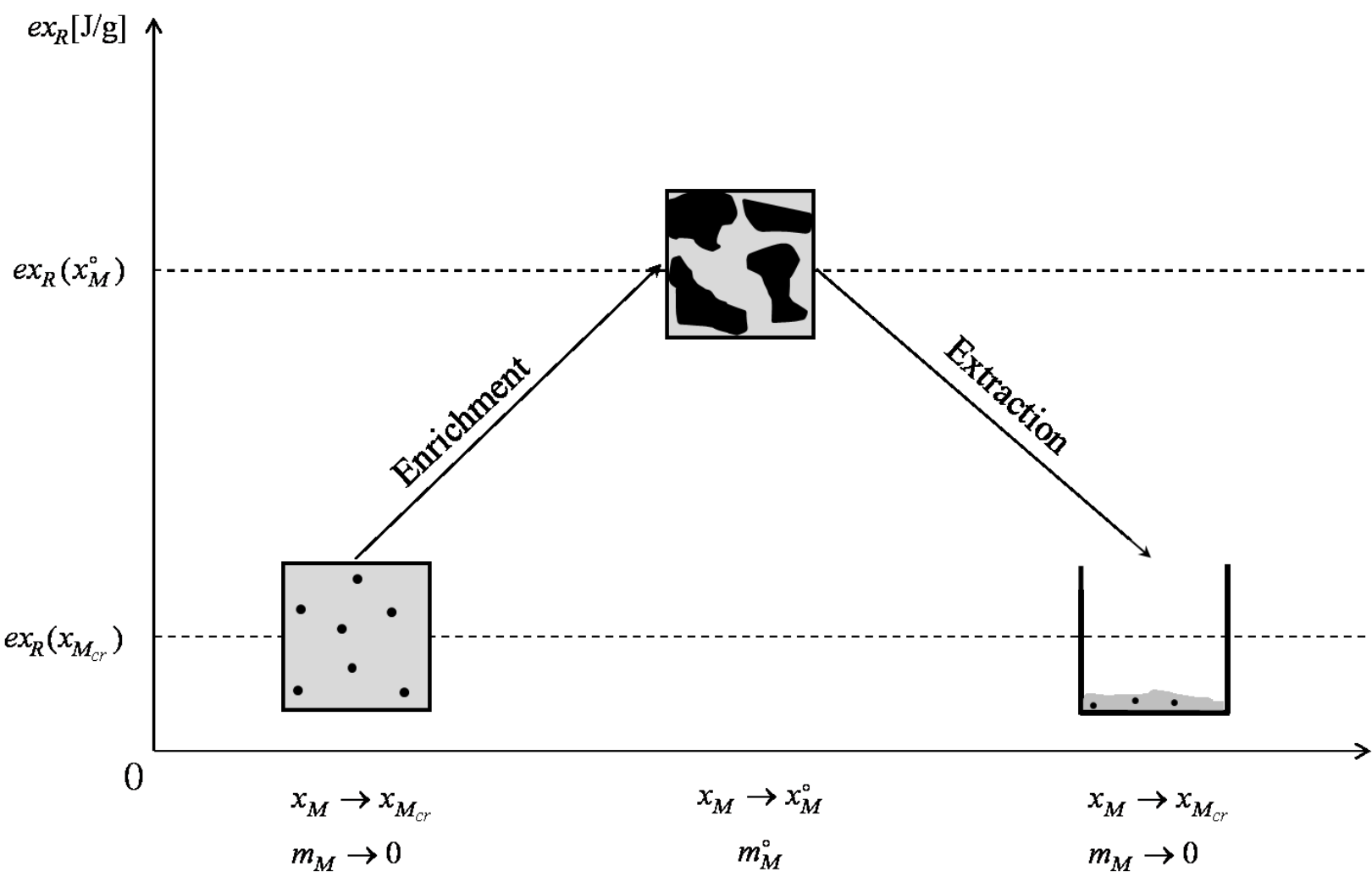


Figure4

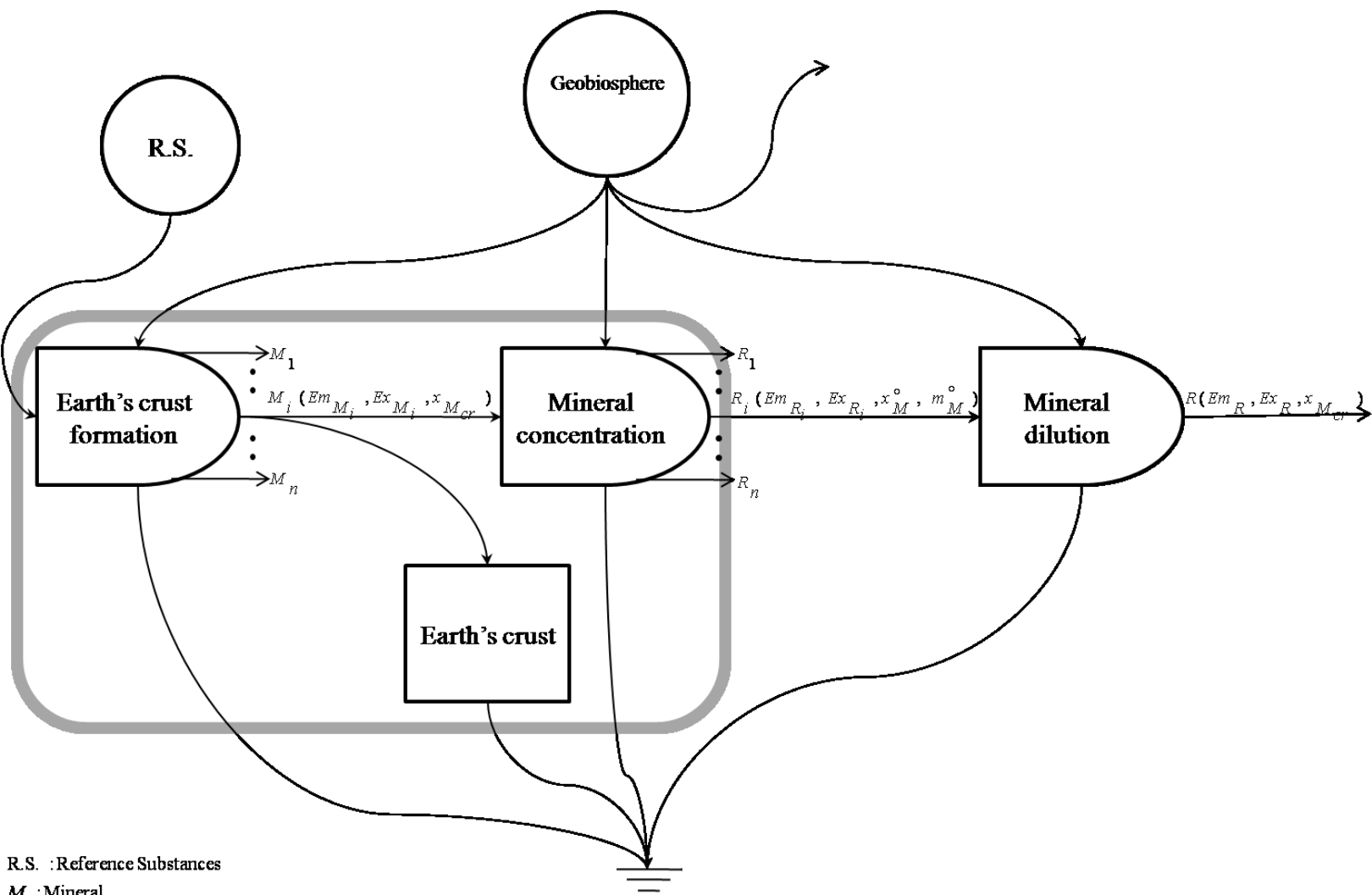
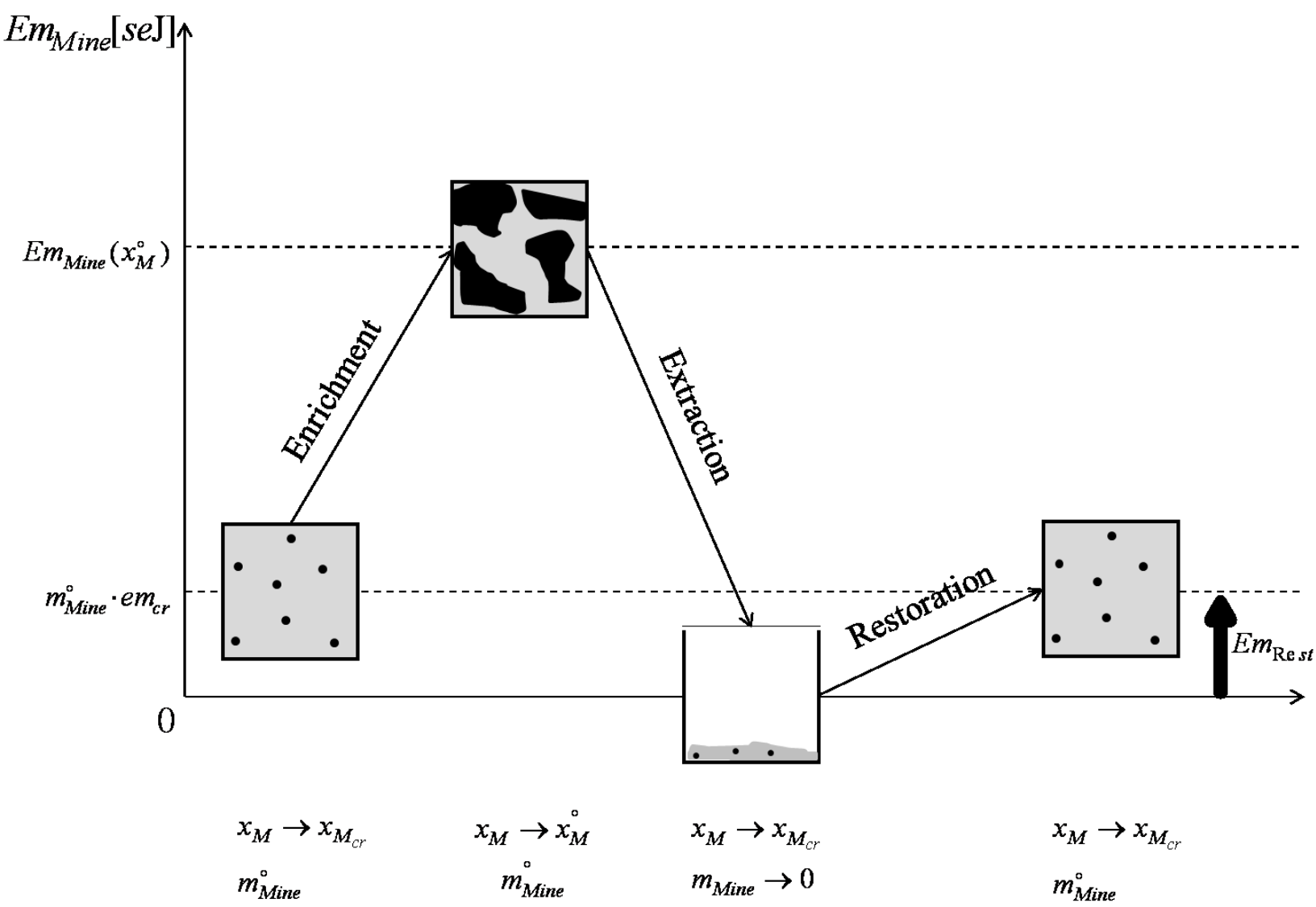


Figure5



m_{cr} [kg]	M_{cr} [g/mol]	ex_{cr} [J/mol]	Ex_{cr} [J]	τ_F [seJ/J]	Em_{cr} [seJ]
1.08E+22	155.2	3.63E+3	2.53E+26	4.2	1.06E+27

Table 1: Thermodynamic and emergetic properties of the Earth's upper crust

Chemical properties of the main commercially used mineral									LIST OF TABLES
Name	Chemical Formula	M_M [g/mol]	$x_{M_{cr}}$ E-6	$OGCE-2$	ER_R	k_{cM}	k_{chM}	ex_{chM} [kJ/m ³]	
Aluminium	Al_2O_3	102	8.00E+04	1.70E+01	2.10E+00	3.96E+02	1	3.49E+01	
Antimony	Sb_2S_3	339.7	2.00E-01	1.00E+01	5.00E+05	2.84E+01	10	2.52E+03	
Arsenic	$FeAsS$	162.8	1.50E+00	2.00E+00	1.33E+04	7.99E+01	10	1.43E+03	
Barium	$BaSO_4$	-	5.50E+02	5.80E+00	1.06E+02	NA	1	-	
Beryllium	$6SiO_2.Al_2O_3.3BeO$	537.6	3.00E+00	4.00E+00	1.33E+04	1.12E+02	1	6.58E+01	
Bismuth	Bi_2S_3	514.2	1.27E-01	5.00E+00	3.94E+05	8.98E+01	10	2.23E+03	
Cadmium	CdS	144.5	9.80E-02	4.00E-01	4.08E+04	8.04E+02	10	7.44E+02	
Cesium	$CsCl$	-	3.70E+00	2.00E+01	5.41E+04	NA	1	-	
Chrome	$FeCr_2O_4$	223.8	3.50E+01	2.30E+01	6.57E+03	3.67E+01	1	1.95E+02	
Cobalt	CoS_2	123.1	1.00E+01	2.00E-01	2.00E+02	1.26E+03	10	1.39E+03	
Copper	$CuFeS_2$	183.5	2.50E+01	5.00E-01	2.00E+02	3.86E+02	10	1.53E+03	
Fluoride	CaF_2	78.1	6.50E+02	1.00E-01	1.50E+00	1.70E+00	1	5.03E+01	
Gallium	$Ga(OH)_3$	-	1.70E+01	1.00E-02	5.90E+00	-	1	-	
Germanium	GeO_2	-	1.60E+00	6.00E+00	3.75E+04	-	1	-	
Gold	Au	197	1.80E-03	1.50E-03	8.33E+03	4.09E+05	1	5.99E+01	
Hafnium	HfO_2	-	5.80E+00	4.00E-02	6.90E+01	-	1	-	
Indium	InS	146.9	5.00E-02	1.00E-02	2.00E+03	-4.39E+01	10	9.13E+02	
Iron	Fe_2O_3	159.7	3.50E+04	5.00E+01	1.43E+01	4.40E+01	1	1.64E+01	
Lead	PbS	239.3	2.00E+01	4.00E+00	2.00E+03	2.12E+02	10	7.41E+02	
Lithium	$LiAlSi_2O_6$	186.1	2.00E+01	3.00E+00	1.50E+03	1.58E+02	1	2.87E+01	
Magnesium	$MgCl_2$	95.2	1.33E+04	1.00E-01	1.00E-01	1.00E+00	1	1.61E+02	
Manganese	MnO_2	86.9	6.00E+02	2.50E+01	4.17E+02	2.84E+02	1	3.49E+01	
Mercury	HgS	232.7	8.00E-02	1.00E-01	1.25E+04	1.71E+03	10	6.79E+02	
Molybdenum	MoS_2	160.1	1.50E+00	3.00E-01	2.27E+03	9.47E+02	1	1.72E+03	

Continued on next page...

Name	Chemical Formula	M_M [g/mol]	$x_{M_{cr}}$ E-6	$OGCE-2$	ER_R	k_{cM}	k_{chM}	ex_{chM} [kJ/m ³]	LIST OF TABLES
Nickel	NiS	90.7	2.00E+01	9.00E-01	4.50E+02	3.37E+02	10	7.66E+02	
Niobium	Nb_2O_5	-	2.50E+01	5.00E-01	1.88E+02	NA	1	-	
Phosphorous	P_2O_5	142	7.00E+02	1.48E+01	2.11E+02	4.39E+01	1	3.59E+02	
Platinum	PtS	-	1.00E-02	1.95E-03	1.95E+03	NA	1	-	
Potassium	KCl	74.56	2.80E+04	1.50E+01	5.77E+04	3.86E+01	1	1.96E+01	
Rhenium	ReS_2	250.3	4.00E-04	3.00E-01	3.00E+06	1.94E+03	10	1.62E+03	
Selenium	SeO_2	-	5.00E+01	2.50E-04	2.50E+01	NA	1	-	
Silicon	SiO_2	60.1	3.08E+05	4.00E+01	1.30E+00	1.89E+00	1	8.20E-01	
Silver	Ag_2S	247.8	5.00E-02	1.00E-02	2.00E+03	7.05E+03	10	7.06E+02	
Sodium	$NaCl$	58.4	2.90E+04	2.00E+01	6.90E+00	3.81E+01	1	1.44E+01	
Tantalum	Ta_2O_5	441.1	2.20E+00	1.00E-01	2.50E+02	1.25E+04	1	4.56E+01	
Tellurium	TeO_2	-	1.00E-03	1.00E-04	1.00E+02	NA	1	-	
Tin	SnO_2	150.7	5.50E+00	4.00E-01	6.36E+02	1.49E+03	1	4.26E+01	
Titanium	$FeTiO_3$	151.7	3.00E+03	1.00E+01	3.33E+01	3.48E+02	1	1.30E+02	
Tungsten	$CaWO_4$	288	2.00E+00	6.00E-01	3.00E+03	3.10E+03	1	7.21E+01	
Vanadium	V_2O_5	182	6.00E+01	6.00E-01	4.29E+01	5.72E+02	1	3.23E+01	
Zinc	ZnS	97.4	7.10E+01	3.50E+00	4.93E+02	6.28E+01	10	7.44E+02	
Zirconium	$ZrSiO_4$	183.3	1.90E+02	2.00E+00	1.05E+02	7.74E+03	1	3.08E+01	

Table 2: Chemical properties of the main commercially used minerals

Dispersed specific emergy of the main commercially used mineral		
Name	Chemical Formula	$em_M(x_{M_{cr}})$ [seJ/g]
Aluminium	Al_2O_3	1.23E+03
Antimony	Sb_2S_3	4.92E+08
Arsenic	$FeAsS$	6.56E+07
Barium	$BaSO_4$	1.79E+05
Beryllium	$6SiO_2 \cdot Al_2O_3 \cdot 3BeO$	3.28E+07
Bismuth	Bi_2S_3	7.75E+08
Cadmium	CdS	1.00E+09
Cesium	$CsCl$	2.66E+07
Chrome	$FeCr_2O_4$	2.81E+06
Cobalt	CoS_2	9.84E+06
Copper	$CuFeS_2$	3.94E+06
Fluoride	CaF_2	1.51E+05
Gallium	$Ga(OH)_3$	5.79E+06
Germanium	GeO_2	6.15E+07
Gold	Au	5.47E+10
Hafnium	HfO_2	1.70E+07
Indium	InS	1.97E+09
Iron	Fe_2O_3	2.81E+03
Lead	PbS	4.92E+06
Lithium	$LiAlSi_2O_6$	4.92E+06
Magnesium	$MgCl_2$	7.40E+03
Manganese	MnO_2	1.64E+05
Mercury	HgS	1.23E+09
Molybdenum	MoS_2	6.56E+07
Nickel	NiS	4.92E+06
Niobium	Nb_2O_5	3.94E+06
Phosphorous	P_2O_5	1.41E+05
Platinum	PtS	9.84E+09
Potassium	KCl	3.51E+03
Rhenium	ReS_2	2.46E+11
Selenium	SeO_2	1.97E+06
Silicon	SiO_2	3.19E+02
Silver	Ag_2S	1.97E+09
Sodium	$NaCl$	3.39E+03
Tantalum	Ta_2O_5	4.47E+07
Tellurium	TeO_2	9.84E+10
Tin	SnO_2	1.79E+07
Titanium	$FeTiO_3$	3.28E+04
Tungsten	$CaWO_4$	4.92E+07

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Name	Chemical Formula	$em_M(x_{M_{cr}})$ [seJ/g]
Vanadium	V_2O_5	1.64E+06
Zinc	ZnS	1.39E+06
Zirconium	$ZrSiO_4$	5.18E+05

Table 3: Crustal specific emergy of the main commercially used minerals

Specific energy of mineral reserves at their ore grade cutoff				
Name	Chemical Formula	$em_R^1(x_M)$ [seJ/g]	$em_R^2(x_M)$ [seJ/g]	$em_R(x_M)$ [seJ/g]
Aluminium	Al_2O_3	3.40E+09	2.84E+08	2.25E+07
Antimony	Sb_2S_3	8.10E+14	6.75E+13	1.86E+10
Arsenic	$FeAsS$	2.16E+13	1.80E+12	8.71E+09
Barium	$BaSO_4$	1.71E+11	1.42E+10	-
Beryllium	$6SiO_2 \cdot Al_2O_3 \cdot 3BeO$	2.16E+13	1.80E+12	1.32E+12
Bismuth	Bi_2S_3	6.38E+14	5.31E+13	1.01E+11
Cadmium	CdS	6.61E+13	5.51E+12	2.86E+12
Cesium	$CsCl$	8.76E+13	7.30E+12	-
Chrome	$FeCr_2O_4$	1.06E+13	8.87E+11	1.15E+10
Cobalt	CoS_2	3.24E+11	2.70E+10	1.18E+10
Copper	$CuFeS_2$	3.24E+11	2.70E+10	1.30E+09
Fluoride	CaF_2	2.43E+09	2.03E+08	5.60E+06
Gallium	$Ga(OH)_3$	9.56E+09	7.97E+08	-
Germanium	GeO_2	6.08E+13	5.06E+12	-
Gold	Au	1.35E+13	1.12E+12	8.35E+18
Hafnium	HfO_2	1.12E+11	9.32E+09	-
Indium	InS	3.24E+12	2.70E+11	-
Iron	Fe_2O_3	2.32E+10	1.93E+09	4.68E+07
Lead	PbS	3.24E+12	2.70E+11	2.66E+09
Lithium	$LiAlSi_2O_6$	2.43E+12	2.03E+11	4.91E+11
Magnesium	$MgCl_2$	1.62E+08	1.35E+07	3.02E+05
Manganese	MnO_2	6.75E+11	5.63E+10	1.92E+10
Mercury	HgS	2.03E+13	1.69E+12	7.23E+12
Molybdenum	MoS_2	3.67E+12	3.06E+11	6.81E+11

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Name	Chemical Formula	$em_R^1(x_M)$ [seJ/g]	$em_R^2(x_M)$ [seJ/g]	$em_R(x_M)$ [seJ/g]
Nickel	<i>NiS</i>	7.29E+11	6.08E+10	3.28E+09
Niobium	<i>Nb₂O₅</i>	3.05E+11	2.54E+10	-
Phosphorous	<i>P₂O₅</i>	3.42E+11	2.85E+10	2.27E+08
Platinum	<i>PtS</i>	3.16E+12	2.63E+11	-
Potassium	<i>KCl</i>	9.35E+13	7.79E+12	2.59E+07
Rhenium	<i>ReS₂</i>	4.86E+15	4.05E+14	1.16E+15
Selenium	<i>SeO₂</i>	4.05E+10	3.38E+09	-
Silicon	<i>SiO₂</i>	2.11E+09	1.76E+08	5.17E+05
Silver	<i>Ag₂S</i>	3.24E+12	2.70E+11	3.70E+13
Sodium	<i>NaCl</i>	1.12E+10	9.32E+08	3.60E+07
Tantalum	<i>Ta₂O₅</i>	4.05E+11	3.38E+10	1.86E+14
Tellurium	<i>TeO₂</i>	1.62E+11	1.35E+10	-
Tin	<i>SnO₂</i>	1.03E+12	8.59E+10	1.02E+13
Titanium	<i>FeTiO₃</i>	5.39E+10	4.50E+09	7.62E+08
Tungsten	<i>CaWO₄</i>	4.86E+12	4.05E+11	4.20E+13
Vanadium	<i>V₂O₅</i>	6.95E+10	5.79E+09	3.32E+11
Zinc	<i>ZnS</i>	7.99E+11	6.66E+10	1.81E+08
Zirconium	<i>ZrSiO₄</i>	1.71E+11	1.42E+10	1.50E+12

Table 4: Specific energies of mineral reserves at their *OGC* calculated by different approaches

Characteristics of Australians mineral reserves							
Mineral reserve	$x_{M_{cr}}$	x_M°	x_M	Δt [yr]	$em_R(x_M^\circ)$ [seJ/g]	$em_R(x_M)$ [seJ/g]	D [%]
Gold	1.80E-09	3.73E-05	2.02E-06	1859-2000	6.76E+22	4.78E+22	29.3
Copper	2.50E-05	2.60E-01	1.33E-02	1844-2004	1.70E+13	1.14E+13	33.0
Nickel	2.00E-05	4.57E-02	1.16E-02	1967-2004	3.07E+13	2.52E+13	17.9
Silver	5.00E-08	3.00E-03	8.00E-04	1884-2004	3.94E+17	3.47E+17	12.0
Lead	2.00E-05	7.80E-01	4.32E-02	1879-2000	2.87E+13	1.98E+13	30.9
Zinc	7.10E-05	1.70E-01	8.50E-02	1905-2004	1.69E+12	1.53E+12	9.3
Iron	3.50E-02	6.80E-01	6.20E-01	1907-2004	4.70E+11	4.50E+11	4.4

Table 5: Characteristics of Australians mineral reserves

x_{Copper}°	m_{Copper}° [kg]	$x_{Copper_{cr}}^{\circ}$	m_{rem} [kg]	$Em_{Mine}(x_{Copper}^{\circ})$ [seJ]	Em_{Rest} [seJ]
0.02	1.84E+11	2.5E-5	1.84E+11	7.26E+20	1.81E+16

Table 6: Emergy loss and mine restoration of US copper reserves

Inflow	$Ex[J/yr]$	$\tau[seJ/J]$	$Em[seJ/yr]$
Solar energy absorbed	3.6E+24	1	3.6E+24
Crustal heat sources	1.6E+20	20300	3.3E+24
Tidal energy absorbed	1.15E+20	72400	8.3E+24
Geobiosphere	3.6E+24	-	15.2E+24

Table 7: Global energy budget of the geobiosphere (Brown and Ulgiati, 2010)