Exergy : A Useful Indicator for the Sustainability of Mineral Resources and Mining

Dr Alicia Valero[1], Dr Antonio Valero[1], Dr Gavin M. Mudd[2,#]

[1]Centre of Research for Energy Resources and Consumption (CIRCE), University of Zaragoza, Spain
[2]Environmental Engineering, Department of Civil Engineering, Monash University, Clayton, Melbourne, Australia [#]Gavin.Mudd@eng.monash.edu.au

Abstract

There is active debate and research around the most suitable indicators to assess the sustainability of mining. The most common approach is to report a range of data for a given mine site (or less preferably, a company total), such as inputs, outputs, benefits and potential costs. The most popular protocol in use (and growing rapidly) is the Global Reporting Initiative (GRI). However, these measures are numerous and still do not allow a single over-arching indicator to be developed. Other measures, such as known mineral resources over time, do not account for critical challenges such as declining ore grades, increasing wastes and poorer quality ores or more difficult mineralogy. By adopting a thermodynamic approach to sustainability, through the concept of 'exergy', it is possible to incorporate into a single measure the effective quality of mineral resources. Exergy involves the assessment of the minimum energy costs involved in producing a mineral resource with a specific chemical composition and concentration from common materials in the environment. The exergy of a mineral resource is evaluated from mineralogic composition, concentration (or ore grade) and, of course, quantity, by multiplying the unit exergies with the tonnes of the resource produced (or consumed). Since exergy is a thermodynamic quantity (ie. energy or joules), it is additive across different minerals, such as iron ore to gold to copper or even oil and gas or coal – making it an ideal indicator to assess mineral resource sustainability at the industry scale rather than the individual mine scale. This paper briefly outlines the theoretical basis for exergy, and then presents a range of commodity case studies showing the application of exergy to the Australian mining industry. Overall, the usefulness of exergy is clearly demonstrated for use as a broad indicator of the sustainability of mineral resources at the national or even global scale.

INTRODUCTION

The concept of ‘sustainable mining’ is a challenging area for sustainability. The very nature of mining is the extraction of ‘finite’ mineral wealth from the earth’s natural capital or stocks – and given that mineral or metal commodities can range in grade from >60% for iron, <0.5% to several percent for base metals down to grams per tonne for precious metals, how can any indicator be used to assess cumulative sustainability over time? This is no easy task, yet it is vital to understanding and predicting the future of the mining industry at a regional or even global scale.

It is the purpose of this paper to review the application of “exergy” accounting to mineral resources and mining. Exergy is the use of thermodynamic accounting to assess, in one quantity, the true energy required to produce minerals or metals from a degraded state in the so called Reference Environment (RE; i.e. an analogue of a depleted natural environment). It allows for the incorporation of the quality, i.e. chemical composition and concentration of a mineral or metal, and can also allow for the state of technology to be assessed through the exergy costs. In this way, exergy makes for a compelling way to examine the true value of mineral resources since it is based on thermodynamics, with units of Joules (J; or equivalent energy units such as tonnes of oil equivalent, ‘toe’). The exergy costs of gold or copper or iron ore mining can therefore be examined in an equivalent indicator – exergy (J) – and trends over time can give significant insights into the sustainability of mining. Thus the paper aims to demonstrate that exergy is indeed an accurate and viable approach to quantifying sustainability in mining at a regional or global scale, using Australia as a detailed case study.

THE THEORY OF EXERGY: A BRIEF REVIEW

This section is only a brief examination of the theoretical basis for exergy accounting. For further details, see Valero (2008) and Valero et al. (2008).

As a result of the application of Thermodynamics to the evaluation of natural resources, and with the support of Thermoeconomics (see a historical overview in Valero and Torres, 2005) a rather new approach called *Exergoecology* was proposed by Valero (1998) as a tool for natural resources accounting. Exergoecology is the application of the exergy analysis (Second Law of Thermodynamics) to the evaluation of natural fluxes and resources on Earth defined from a Reference Environment (RE). It allows to value resources, according to the physical cost, i.e. the amount of exergy that would be required to obtain them from the materials contained in a hypothetical environment where each element has its lowest reactivity compatible with the mineral’s abundance on Earth (Szargut et al, 1988). A mine, like an iceberg or a cloud has exergy with respect to this RE. If society would want to replace an iceberg or a cloud using current available technology, immense amounts of additional exergy would be required. Using the exergy analysis combined with the rules for exergy cost accounting provided by Thermoeconomics, it is possible to get reasonable estimates. Exergoecology provides this analysis, by quantifying the physical cost (J) of replacing natural resources from a degraded state in the so called RE, to the conditions in which they are currently presented in Nature.

Figure 1 shows in a schematic way the processes involved in the production of a certain raw material like iron or copper. During millions of years, Nature has formed and concentrated minerals through a large number of geological processes such as magmatic separation, hydrothermal, sedimentary, residual, etc. (Chapman and Roberts, 1983) forming the currently existing natural stock. The concentrated mineral deposits serve as a material and fuel reservoir for society. The extraction of materials implies an obvious reduction of the natural stock in terms of the minerals extracted from the mines and the fossil fuels required for the mining processes. Those extracted minerals are concentrated and further refined to obtain the desired raw materials, for which additional quantities of fuels and minerals are required. This way, the natural stock stored in the Earth’s crust goes into the hands of society as technological stock. When the useful life of products finishes, they end up as wastes – either as pollution or disposed of in landfills – or are recycled. When materials become degraded and dispersed, they arrive at similar conditions as in the RE. Consequently, the costs associated to obtain the raw material from the minerals dispersed in the RE would include the natural processes of concentrating and forming minerals into the mineral deposits (replacement costs, J) and those associated with mining and refining the minerals (extraction and processing costs, J). In the case of recycling, the cost to obtain the raw material is restricted to the processing of the substance, thereby saving the natural replacement costs as well as the mining and concentration costs.

Figure 1: Processes involved in the production of a raw-material

It is important to note the difference between extraction and replacement costs. The former assesses the resource from the mine to market. However, the latter assess the resource from the degraded Earth or RE to the mine. As Naredo (1987) argues, economy puts value to natural resources considering their extraction costs and not their replacement costs. Therefore, extraction and not recovery or recycling is fostered and optimized. This enhances the efficiency of the extraction processes, facilitating the market availability of these substances and further increasing their scarcity, rather than saving resources for future generations. The Exergoecological approach shifts the anthropogenic view of the value of resources to the Nature's point of view based on thermodynamics. This way, the Earth is not considered as an infinite reservoir of minerals. On the contrary, it is seen as a provider with a finite amount of exergy resources, whose extraction implies the use of further exergy resources. The primary objective of this field of research is thus to extend the exergy analysis until the origin of all the natural resources at stake in a production process are accounted for.

Exergy and exergy cost assessment of minerals

The most important features that fix the value of a mineral resource are on one hand its chemical composition and on the other hand its concentration – both characteristics which can be assessed with the single indicator of exergy.

The chemical composition of a substance is the key factor for fixing the final use of the resource. Furthermore, it has a direct influence on the energy required for processing the mineral. For instance, the energy required to extract pure copper from a sulphide is significantly smaller than from an oxide, therefore copper sulphides such as chalcopyrite ($CuFeS_2$) are preferred as copper ores (see Gerst, 2008). The chemical exergy can be calculated using the following well known expression (Szargut et al., 1988):

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

where $b_{ch\ el,k}$ is the standard chemical exergy of the elements that compose the mineral and can be easily found in tables, ν_k is the number of moles of element k in the mineral and ΔG is the Gibbs free energy of the mineral.

The minimum amount of energy – exergy – involved in concentrating a substance from an ideal mixture of two components is given by the following expression (Faber and Proops, 1991):

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

Where b_c is the concentration exergy, x_i is the molar concentration of substance i, R is the gas constant (8.3145 J/mol•K) and T_0 is the reference temperature (298.15 K). This formula is only strictly valid for ideal gases. When there is not chemical cohesion among the substances, it remains valid for solid mixtures. The cohesion energy is the minimum exergy needed to break the weak binding forces among solids such as hydrogen bond, surface and hydration forces as opposed to strong ones like crystal or chemical bonds. Notwithstanding it, they are strong enough to require physical separation processes like crushing, grinding, or floatation. So deviations of this formula can be expected, however it does provide a reasonable approximation of the behaviour of b_c. Further research is currently in progress to overcome this step. The difference between the concentration exergies obtained with the mineral concentration in a mine x_m and with the average concentration in the Earth's crust x_c is the minimum energy that Nature had to spend to bring the minerals from the concentration in the reference state to the concentration in the mine. Note also the log-normal behaviour of this formula. The additional exergy, Δb, required for separating an additional Δx in a mixture depends on x, and tends to infinity when $x \rightarrow 0$. This means that complete purification is impossible or that infinitesimal pollution is infinitely easy. The more separation we want, the more exergy is expended per unit of additional separated material Δx. So scarcity behaves log-normal, and each time we disperse materials, the exergy needed for recovering them from the environment increases exponentially. Therefore, scarce materials like Au or Ag have a much higher natural concentration exergy than common ones like Si, Al, or Fe.

This way, the total replacement exergy (b_t), i.e. its natural exergy, representing the minimum exergy required for restoring the resource from the RE to the initial conditions in the mineral deposit, is calculated as the sum of the chemical and concentration exergy components (Eq.3).

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

However, a study based only on reversible processes (minimum replacement exergies) would ignore technological limits. Results show that, in general, the real energy requirements are tens or even thousands of times greater than the exergy content of the mineral (Valero and Botero 2002). For instance, the minimum total exergy of bauxite calculated with Eqs. 1 and 2 is 0,41 GJ/t, whereas, the actual exergy required to reproduce bauxite with the composition and concentration found in nature with available technology is about 735 GJ/ton.

The calculation of the exergy replacement costs b_t^* of the resource, representing the actual exergy required to replace the resource from the RE to its initial conditions, with current available technology commonly have two contributions,

$$b_t{}^{*} = k_{ch}\cdot b_{ch} + k_c\cdot b_c \qquad (4)$$

its chemical cost ($k_{ch}\cdot b_{ch}$), accounting for the chemical production processes of the substance, and its concentration cost ($k_c\cdot b_c$), accounting for the concentration processes. Variable k (dimensionless) represents the unit exergy replacement cost of a mineral. It is defined as the relationship between the energy invested in the real obtaining process ($E_{real\_process}$) for either refining (k_{ch}) or concentrating the mineral (k_c), and the minimum energy (exergy) required if the process from the ore to the final product were reversible ($\Delta b_{mineral}$).

$$k = \frac{E_{real\_process}}{\Delta b_{\mathrm{min}eral}} \qquad (5)$$

For instance, for the calculation of the unit replacement cost for concentrating bauxite from the crustal to mine conditions (k_c), it is assumed that the same technology for the concentration of Al_2O_3 from silicate minerals in common rocks can be applied. Bravard et al. (1972) estimated that 43170 BTU/lb of aluminium or 51.9 GJ/ton of Al_2O_3 is required to produce Al_2O_3 from the clay. The minimum exergy required to concentrate Al_2O_3 from the crustal concentration x_m=0.46 to the refining concentration x_r=0.90 is equal to 0.027 MJ/kg (calculated with Eq. 2). Consequently, the unit exergy concentration cost is calculated as: k_c=51/0.027=1875

Table 1 shows the unit exergy replacement costs of the minerals considered in this paper. These values have been updated by the authors from Valero and Botero (2002).

Table 1: Unit exergy costs of seven base-precious metals (updated from Valero and Botero, 2002)

Another very important application of exergy is the representation of the 'Hubbert' peak (traditionally used for estimating the peak of production of fossil fuels) to non-fuel minerals (eg. Hubbert, 1956). The bell-shape curve is better suited to minerals, if it is fitted with exergy over time instead of mass over time. Oil quality keeps nearly constant with extraction, whereas other non-fuel minerals do not (mineral concentration decreases as the mine is being exploited). Therefore exergy is a much better unit of measure than mass, since it accounts not only for quantity, but also for ore grades and composition. Moreover, if the Hubbert model is applied to the exergy replacement costs explained below, the technological factor of extracting and refining the mineral is also taken into account. In short, the well known bell-shaped curve (presented below in Eq 6) can be fitted to the exergy or exergy replacement cost consumption data provided, in order to estimate when mineral production will start declining.

$$f(t) = \frac{R}{b_0\sqrt{\pi}} e^{-\frac{(t-t_0)}{b_0}} \qquad (6)$$

Where parameters b_0 and t_0 are the unknowns and R the economic proven reserves of the commodity. In our case, we represented the yearly exergy replacement cost loss of the commodity calculated with Eq. 5 vs. time, and determined the best-fit parameters for by Eq. 6 using a least squares procedure. The maximum of the function is given by parameter t_0, and it verifies that $f(t_0) = \frac{R}{b_0\sqrt{\pi}}$. The mathematical application used in this study is ‘cftool’ from the software Matlab 7 (MathWorks, 2009).

The next section presents a case study of the exergy replacement costs of the main minerals in Australia.

CASE STUDY : EXERGY AND THE AUSTRALIAN MINING INDUSTRY

The exergoecological method was applied in this study to Australian mines for two reasons:

1) a major study of Australian mining data was recently published by Mudd (2007a)
2) Australia is a major mineral producer and exports numerous commodities around the world.

Given the availability of data, Australia is therefore an excellent case study for exergoecological analysis of minerals and metals.

The exergy of seven important metals throughout their mining history in Australia has been obtained: Au, Cu, Ni, Ag, Pb, Zn and Fe. Eq. 1 was used for calculating b_{ch}. The chemical exergies of the elements generated from the RE defined by Szargut et al. (2005) were used as the independent variables in Eq 1. The concentration exergy b_c was calculated with Eq. 2. The value of x_c was taken from the latest geochemical study of the Earth’s continental crust from Rudnick and Gao (2004).

Figures 2 and 3 show the cumulative minimum exergy consumption over time on the left axis (in toe or ktoe) and the ore grade trend on the right axis for seven metals (Cu, Ni, Pb, Zn, Au, Ag, Fe). The graphs reveal that consumption of all commodities has increased continuously, following a general exponential trend. The quality of Australian mines, or in other words, their ore grade trends, have been notably reducing throughout the last century. This implies an even greater loss of the mine's exergy and, importantly, increasing production of tailings.

Figure 2: Ore grade and cumulative exergy consumption of the Australian mining industry – copper, nickel, lead, zinc, gold and silver

Figure 3: Ore grade and cumulative exergy consumption of Australian iron mines

Table 2 summarises the results obtained from this study, showing the quantity of metal lost in terms of Mtoe, the exergy cost decrease of the economic demonstrated reserves throughout the period of time considered, the depletion degree of the commodities (%Reserves loss) and the number of years estimated until complete depletion occurs if the consumption rate remains as in 2007 (reserves-to-production or R/P ratio expressed in exergy terms). The degree of depletion is estimated by the fraction of cumulative exergy loss by 2007 and divided by the cumulative exergy loss by 2007 plus the remaining exergy reserves in 2007.

Table 2: Reserves data and cumulative exergy losses in the Australian mining industry

It must be stressed that 2007 reserves may increase as new mines are discovered and as technological development allows the exploitation of mines with lower ore grades. Conversely, the future changes may lead to some reserves being reclassified as uneconomic due to prevailing economic conditions, technological failure (eg., Cawse, Bulong; see Mudd, 2007b) or other reasons (eg. carbon trading or taxes). In fact the general trend observed in Australia is that resources have increased over time (Mudd, 2007a,b). However, as Chapman and Roberts (1983) argue, the world is now more developed and better explored, and it is difficult to find regions worthy of intensive exploration efforts (eg. gold; see Mudd, 2007c). This suggests that the process of discovery may be slowing down. Thus, although metal and mineral reserves have been assumed to be constant for illustrative purposes in this paper, in reality they will continue to evolve over time.

Accordingly, the most depleted commodities are in decreasing order: gold, silver and lead experiencing a decrease of 66%, 63% and 63%, respectively. If the rate of consumption remains the same as in 2007, the reserves will last respectively 24, 24 and 35 years. The zinc industry has extracted about 52% of its reserves. At the same production rate, there will be enough reserves for 30 years. Finally, copper, iron and nickel commodities are the least depleted: 25%, 21% and 14% respectively of the present exergy reserves have been extracted.

At current extraction rates, Cu, Fe and Ni reserves would last for 68, 63 and 127 years respectively.

Since exergy is an additive property, the total exergy cost decrease of the Australian metals studied can be calculated. Although the quantity extracted of all commodities in terms of mass cannot be summed up (gold and silver are extracted at rates of hundreds of tonnes per year, whereas the other metals at rates of thousands or millions of tonnes/year), the order of magnitude in terms of exergy cost is similar for all commodities and its sum gives valuable information. B_t*, the energy replacement costs, obtained for all metals listed in Table 2 is equal to 6142 Mtoe: 45.5 times the 2007 primary energy consumption of Australia at 5641 PJ (or 135 Mtoe) (ABARE, 2008).

Additionally, the exergy replacement costs of non-fuel minerals can be compared to those of fossil fuels. The exergy of fossil fuels can be approximated with no significant error to the High Heating Value (HHV). In this way, one can compare with a single unit, such as exergy, the total loss of mineral stock in a country or even in the whole world. Figure 4 shows the loss of mineral capital in Australia due to the production of coal, oil, natural gas and the metals discussed above. The production of fossil fuels has been obtained from BGS statistics (BGS, various years). As can be seen, the production of iron implies a similar degradation of Australia's mineral capital as coal. Oil and natural gas have a slightly lower order of magnitude, while the rest of the studied metals constitute a small fraction of the total.

Figure 4: Decrease of Australia's mineral exergy stock, 1969 to 2007

The Hubbert peak applied to Australian minerals

The Hubbert peak model was applied to the exergy cost of the non-fuel minerals listed above and to the exergy of the main fossil fuels produced throughout Australia's mining industry (coal, oil and natural gas), shown in Figure 5 (including correlation coefficients).

The application of the Hubbert peak model to the exergy reserves of the Australian minerals considered was satisfactorily applied (correlation coefficients in brackets) to gold (86.26%), copper (97.59%), nickel (92.05%), iron (97.10%), coal (99.48%), oil (96.23%) and natural gas (98.94%). That was not the case for commodities silver, lead and zinc since the correlation coefficients of the curves were slightly lower at 79.85%, 88.52% and 95.99%, respectively. Since the production of these three metals are tightly connected (eg. Pb-Zn-Ag ores), this implies that their production patterns do not follow the general behaviour of other commodities. In addition, Hubbert curves assume symmetrical production behaviour which is often not the case due to accelerated mining during boom times (as suggested by the most recent years being significantly above their respective curves in Figure 5). Finally, economic reserves are assumed to be constant, which recent history shows is not the case as reserves commonly increase for most commodities (see Mudd, 2007a,b).

Using the most recent economic demonstrated reserves of the listed minerals, the Hubbert peak model predicted that the maximum production has been already reached for zinc (2008), gold (2006), silver (2005), lead (1996) and oil (1997). Copper will reach the peak in 2020, natural gas in 2025, iron in 2026, nickel in 2040, and finally coal in 2048. In Figure 5, we have plotted the annual exergy replacement costs of all mineral commodities over time and have applied the Hubbert's bell shape curves, including a combined cumulative curve for all commodities analysed. This type of representation will be named here as "Exergy countdown", since it shows in a very schematic way the amount of exergy resources available and the possible exhaustion behaviour that they will follow. The curves provided for lead, zinc and silver should be noted with caution, since as stated before, the model does not satisfactorily apply for that group of metals.

Figure 5: Exergy countdown of the main minerals produced in Australia

In Figure 5, the bell shaped curves of all fuels plus those of iron and copper are represented. As can be seen, in irreversible exergy terms, coal is the most abundant resource, followed by iron. Until the end of the first decade of the 21st century, both commodities will be extracted at similar rates. However, the predicted peak of iron production in the second decade of the 21st century will slow down the extraction of the metal, while coal will clearly dominate the mineral extraction in Australia. Figure 5 also shows the significantly lower amount of the exergy cost reserves of natural gas and oil compared to iron and coal. Similar observations can be seen for the rest of the metals considered. It is interesting to notice that although copper is the most abundant commodity in exergy terms (apart from iron), the greater extraction rate of that mineral will result in it having a faster depletion than that of nickel. Similarly, although the exergy cost reserves of zinc and nickel are similar, the greater extraction rate of zinc implies that the peaking year of that metal will be reached before that of nickel. The graph also shows the smaller relative amount of the commodities of lead, gold and silver. The exergy countdown diagram of a country allows us to predict future mineral productions and the depletion degree of the commodities. This way, for instance, we can forecast according to our results, that in year 2050, about 64% of the total considered mineral reserves in Australia will be depleted in terms of exergy. Particularly, gold will be depleted at 99.9%, copper at 90.3%, lead at 87%, zinc at 97.3%, nickel at 60.4%, iron at 80%, coal at 52.4%, oil at 95.9% and natural gas at 85.2%.

It must be pointed out, that the latter minerals are not the only ones extracted in Australia. Other minerals such as uranium, alumina, manganese, tin, diamonds and mineral sands are also produced. The lack of historical information on ore grade trends for most of these commodities prevents a similar thorough exergoecological analysis. Additionally, more mineral resources could be found in the future, thereby shifting the peaking year to later dates. However, repeating the same analysis assuming that the current proven reserves will double, would shift the peak only by 15 to 30 years. Hence, the figures provided are reasonable to provide a reasonable view of the magnitude of the global exergy degradation in Australia due to mineral extraction.

CONCLUSIONS

This paper has showed that exergy analysis could be used as a tool for assessing mineral resources on Earth. Unlike other economical or physical evaluations, the property exergy takes into account all facets that make a natural resource valuable. Accordingly, in a single indicator, it is possible to assess quantity, chemical composition and concentration. Furthermore, through unit exergy costs, it is possible to assess the state of technology. Another advantage of exergy is that it can be summed up for all minerals, whereas it is impossible with mass: i.e. tonnes of copper plus tonnes of oil.

As a case study, we have applied the exergoecological approach to the assessment of the degradation of gold, copper, nickel, silver, lead, zinc and iron in Australia throughout their mining history until 2007. Analysis has shown that more than 50% of gold, silver and lead have been mined, making the mining of these metals unsustainable in the long-term. The mining of nickel, iron and copper is taking place in Australia at a relatively slower rate, with significantly less than the majority mined to date and are arguably being mined at a more sustainable rate. The sustainability of zinc can be ordered between both groups. In addition, analysis also showed that the exergy replacement cost of the studied mineral capital extracted in Australia is equivalent to 45.5 times Australia’s 2007 primary energy consumption. This indicates a very significant value of lost natural capital.

The “Exergy countdown” graphs provide a practical representation of the mineral reserves available and the possible extraction behaviour of the commodities. With the exergy countdown, we have predicted that by the year 2050 about 64% of the main mineral commodities produced in Australia will be depleted. Moreover, except for coal, iron and nickel, more than 85% of the mineral reserves will be effectively exhausted by then.

The extraction of minerals produces a significant exergy decrease in the natural stock of our planet. Conventional economics only accounts for the energy required in the extraction and refining processes - whereas a fair accountability of resources should also take into account 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 production plus the exergy replacement costs of the extracted non-fuel minerals as shown in Fig. 8.

The exergy analysis together with the exergy countdown of minerals could constitute a useful prediction tool for assessing the degradation degree of non-renewable resources. However, this technique requires world trends of natural resources production and consumption, and trends of ore grades and mineral reserve projections which are often not readily available. Better compilation of world mineral data would allow for more accurate accounts of natural capital using exergoecological methods.

REFERENCES

ABARE, 2008. *Energy in Australia 2008*. Australian Bureau of Agricultural & Resource Economics (ABARE), Canberra, Australia (www.abare.gov.au)

BGS, Various years. *World Mineral Statistics*. British Geological Survey, UK.

Bravard JC, Flora B and Portal C, 1972. Energy expenditures associated with the production and recycling of metals, report ORNL-NSF-EP-24. Oak Ridge National Labs. 87pp.

Chapman, P F, Roberts F, 1983. *Metal Resources and Energy*. England: Butterworth & Co.

Faber, M and Proops, J L, 1991. *National accounting, time and the environment*. New York: Columbia University Press: 214-233.

Gerst, M D, 2008. Revisiting the cumulative grade-tonnage relationship for major copper ore types. *Econ Geol*, 103(3): 615-628.

Hubbert, M K, 1956. Nuclear Energy and the Fossil Fuels. Proc. *“Spring Meeting, Southern District, Division of Production, American Petroleum Institute”*, San Antonio, Texas, USA, March 1956, 57 p.

MathWorks, 2009. *MatLab 7*. MathWorks Inc (www.mathworks.com).

Mudd, G M, 2007a. *The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications*. Joint Research Report Mineral Policy Institute (MPI) and Department of Civil Engineering, Monash University, Research Report 5, Australia (civil.eng.monash.edu.au/about/staff/muddpersonal/rr5/).

Mudd, G M, 2007b, An Analysis of Historic Production Trends in Australian Base Metal Mining. *Ore Geol Rev*, 32(1-2), pp 227-261.

Mudd, G M, 2007c, Global Trends in Gold Mining : Towards Quantifying Environmental and Resource Sustainability? *Res Pol*, 32(1-2), pp 42-56.

Naredo, J M, 1987. The economy in evolution - History and perspectives of the basic characteristics of the economic thinking (La economía en evolución. Historia y perspectivas de características básicas del pensamiento económico). Siglo XXI. (In Spanish).

Rudnick, R L and Gao, S, 2004. Composition of the Continental Crust, in Treatise on Geochemistry – The Crust (vol. 3) , pp 1-64 (Elsevier Pergamon).

Szargut, J, Morris, D and Steward, F, 1988. *Exergy analysis of thermal, chemicals and metallurgical processes*. New York: Hemisphere Publishing Corporation.

Szargut, J, Valero, A, Stanek, W and Valero, Al, 2005. Towards an international legal reference environment, in *Proceedings of ECOS 2005* (eds: S Kjelstrup, J E Hustad , T Gundersen, A Rosjorde and G Tsatsaronis) pp 409-420 (Norway: Trondheim).

Valero, A, 1988. Thermoeconomics as a conceptual basis for energy-ecological analysis, in *Advances in Energy Studies – Energy Flows in Ecology and Economy* (ed: S Ulgiati) pp 415-444 (Roma: Musis).

Valero, Al, 2008, Exergy Evolution of the Mineral Capital on Earth. PhD Thesis, University of Zaragoza, Spain, (www.exergoecology.com/Members/aliciavd/PhD_Alicia_Valero.pdf)

Valero, A and Botero, E, 2002. Exergetic evaluation of natural mineral capital (2): Application of the methodology to current world reserves, in *ECOS 2002* (eds: G Tsatsaronis, M Moran, F Cziesla and T Bruckner), pp 62-68.

Valero, A and Torres, C, 2005. Thermoeconomic Analysis. Exergy, Energy System Analysis, and Optimization, in *Encyclopedia of Life Support Systems (EOLSS)*, Developed under the Auspices of the UNESCO. Eolss Publishers, Oxford, UK; Online encyclopedia: www.eolss.net (Retrieved 19 May 2008).

Valero, Al, Valero, A and Arauzo, I, 2008. Evolution of the decrease in mineral exergy throughout the 20th century. The case of copper in the US. *Energy*, 33(2): 107-115.

TABLES

Metal	k_c	k_{ch}
Ag	7041.8	1
Au	422879.0	1
Cu	343.1	80.2
Fe	97.4	5.3
Ni	431.8	58.2
Pb	218.8	25.4
Zn	125.9	13.2

Table 1: Unit exergy costs (dimensionless) of seven base-precious metals (updated from Valero and Botero, 2002)

Mineral	Time period	R/P, years	%Reserves lost	B_t* lost, Mtoe
Au	1859 - 2007	24	66	11.60
Cu	1844 - 2007	68	25	119.83
Ni	1967 - 2007	127	14	31.62
Ag	1884 - 2007	24	63	2.41
Pb	1859 - 2007	35	63	44.89
Zn	1897 - 2007	30	52	111.61
Fe	1907 - 2007	63	21	5820.34
TOTAL				6142.31

Table 2: Reserves data and cumulative exergy losses in the Australian mining industry

FIGURES

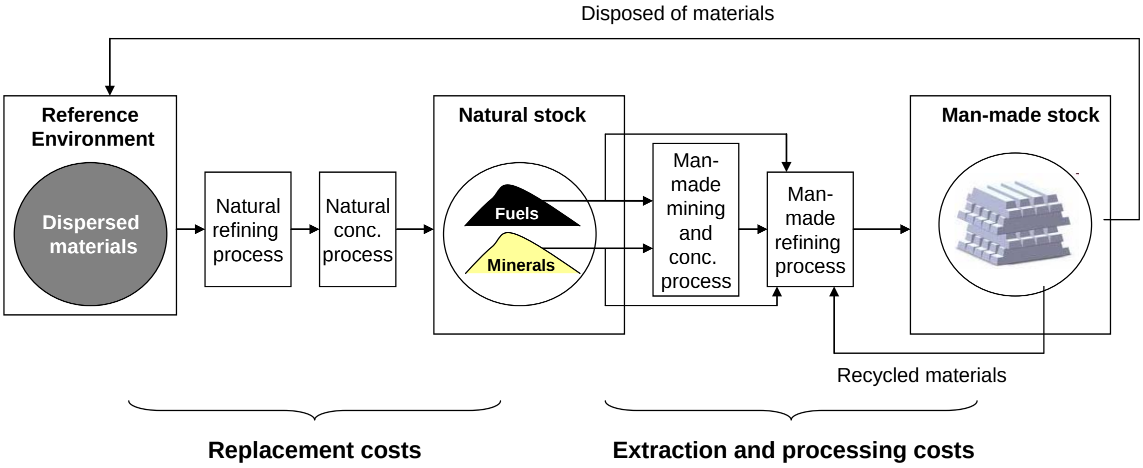

Figure 1: Processes involved in the production of a raw-material

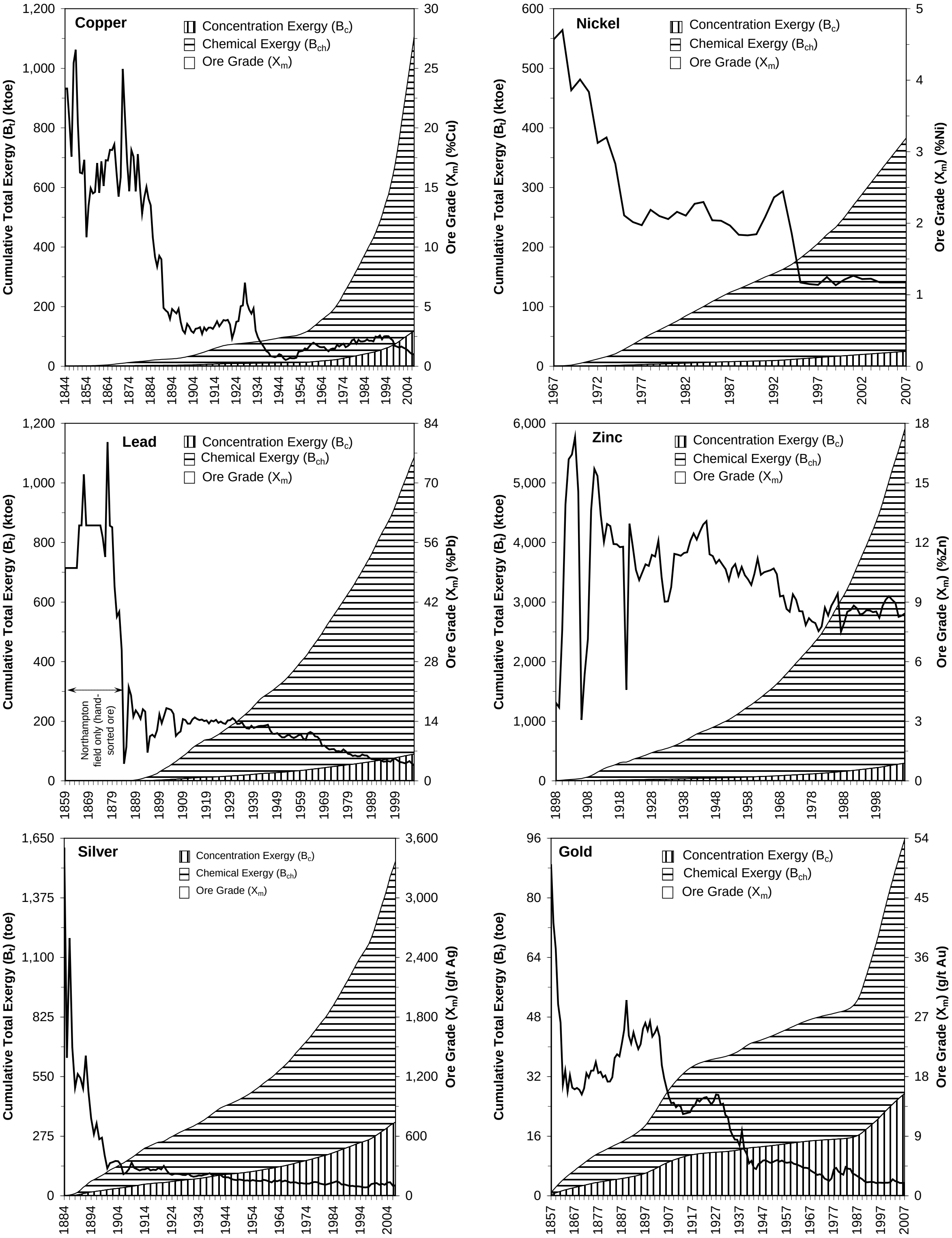

Figure 2: Ore grade and cumulative exergy consumption of the Australian mining industry – copper, nickel, lead, zinc, silver and gold

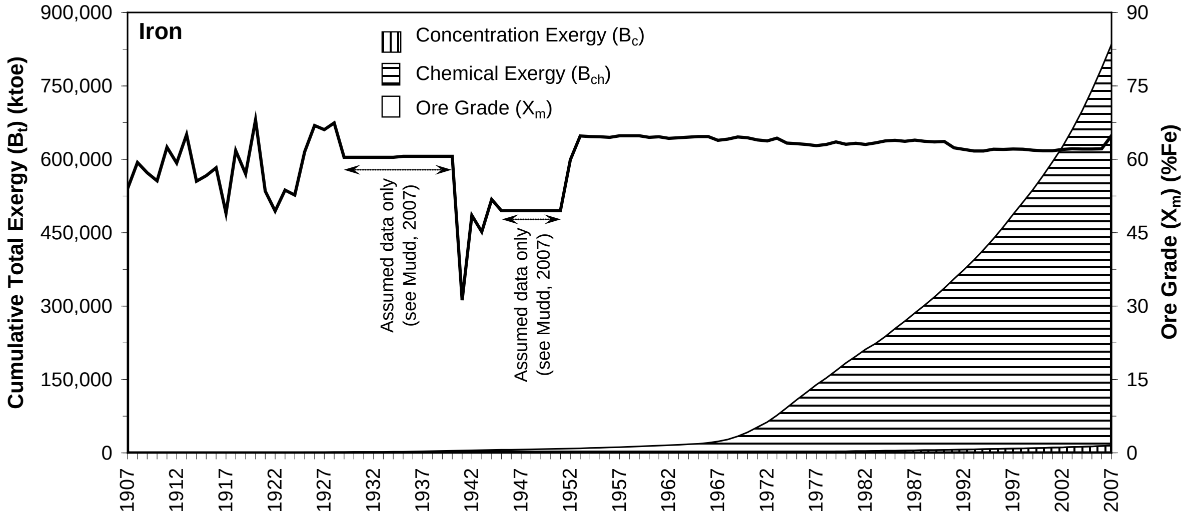

Figure 3: Ore grade and cumulative exergy consumption of Australian iron mines

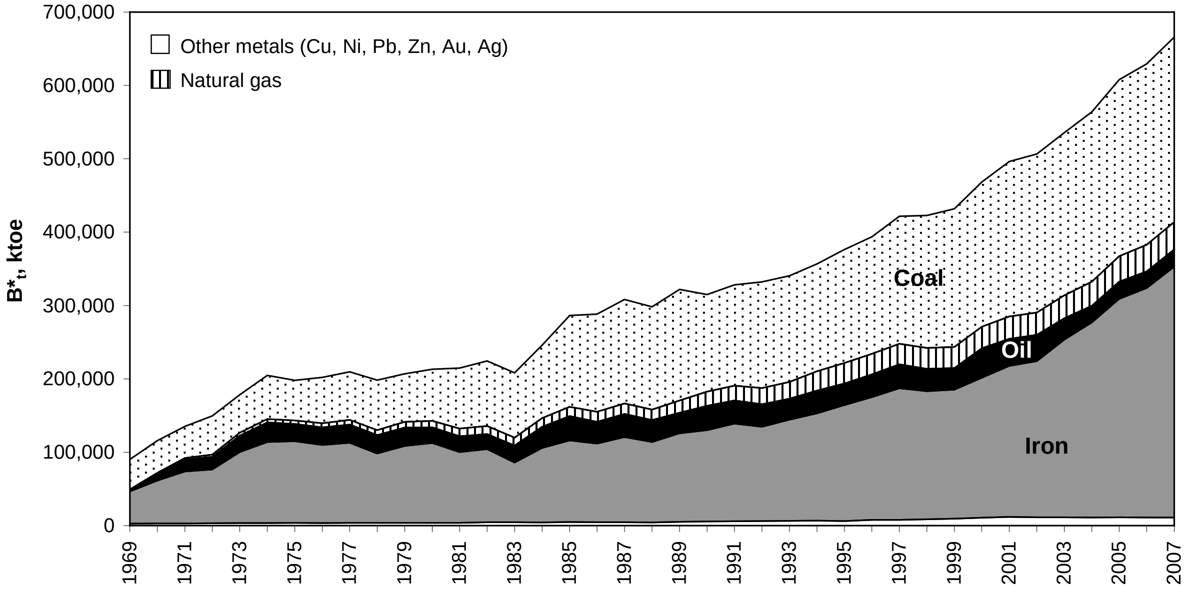

Figure 4: Decrease of Australia's mineral exergy stock, 1969 to 2007

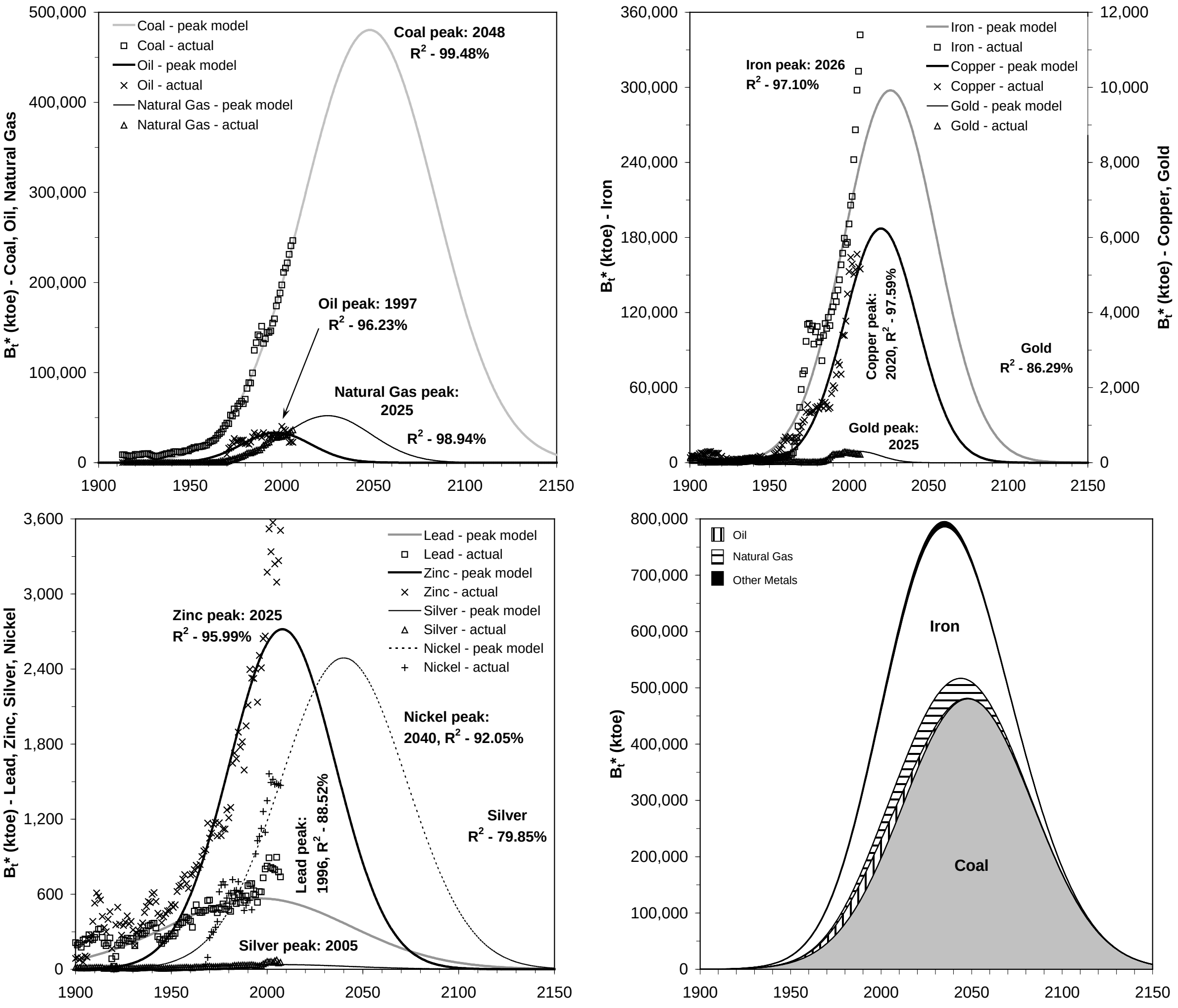

Figure 5: Exergy countdown of the main minerals produced in Australia