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Depletion of the non-renewable natural resource reserves in copper, zinc, lead and aluminium production

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ABSTRACT

Depletion of the world's copper, zinc, lead and aluminium resources is examined using Cumulative Exergy Consumption (CExC) and thermo-ecological cost concepts. Due to a short projected term of availability of the copper, zinc and lead resources (20–30 years) and unavoidable consumption of primary energy (oil, coal, natural gas) the problem of efficiency and economics of the currently used and future technologies is important. It is important that the metallurgy industry is efficient because it can be a significant contribution to Gross National Product and energy consumption in countries where metal production occurs. For example, to get the maximum value from copper deposits, the proper and most efficient technology (of many) should be chosen. The authors proposed a minimum value of Cumulative Exergy Consumption (CExC) as the criterion for the recommended technology. Based on this criterion we conclude that, for example, pure copper cathode production by flash smelting technology is the best technology.

1. Introduction

Consumption of the non-renewable natural resources that are important for human activities and development of our civilization has rapidly expanded in the last decade. The observed depletion of non-renewable resources is dangerous for the future and for world economic stability. As Tilton stated (Tilton, 2003) "*Since the early 70's the availability of non-renewable natural resources over a long term – the period spanning two centuries – has intrigued our society. Without adequate supplies of oil, natural gas and coal, it is difficult to imagine modern civilization as we know it. Many people consider resources availability as one of the major challenges facing humanity along with nuclear war, population growth and environmental preservation.*"

Similar opinions have been expressed by others (Ayers, 1979, 2010; Valero et al., 2008; Lior, 2008a).

Tilton (2003) made estimates for a number of important metals, indicating that in the next 20–30 years scarcity may occur (Table 1).

Countries whose economy relies on metal production, eg. Chile and Poland for copper, will be threatened by exhaustion of reserves in coming decades. Metals such as copper, lead, zinc and aluminium may be produced using different methods. A challenge therefore exists in how to choose the best technology from technological and economical points of view. Many criteria have been proposed – minimization of the consumption of natural resources, maximization of energy efficiency (minimum driving energy) and minimization of metal waste. In this paper, we analyse shaft furnace and flash smelting of copper, ISP shaft furnace technology and the hydrometallurgical method in the case of zinc and lead and finally aluminium via the electrolysis process. It is proposed to use Cumulative Exergy Consumption (CExC) as a measurement of depletion of non-renewable natural resources containing both the metal deposit and primary energy resources. Differences in exergy consumption are the result of different kinds of driving energy – coal, coke, natural gas, electric energy. Additionally, the concept of thermo-ecological cost and entropy generation rates are calculated for all elementary processes to be used as additional criteria. Finally, metal waste is estimated.

2. Why exergy?

Historically the concept of exergy, as available energy, was introduced into thermodynamics by Gouy (1889) and then into

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Table 1
Life expectancies of world reserves (Tilton, 2003).

Mineral commodity	Reserves (t)	Average annual primary production (t)	Life expectancy in years at free growth rate in primary production		
			0%	2%	5%
Aluminium	2.5×10^{10}	1.2×10^{8}	202	81	48
Copper	3.4×10^{8}	1.2×10^{7}	28	22	18
Lead	6.4×10^{7}	3.1×10^{6}	21	17	14
Zinc	1.9×10^{8}	7.8×10^{6}	25	20	16
Nickel	4.6×10^{7}	1.1×10^{6}	41	30	22

engineering thermodynamics by Keenan (1951). The term of exergy was proposed by Zoran Rant (Rant, 1956) to express the quality of energy (see also Gaggioli, 1998). The word – *exergy* – was taken from the Greek – *ex ergon* – which means *"from work"*. Exergy is synonymous with *availability, available energy, utilizable energy, reversible work and ideal work*. Generally speaking, exergy is energy that is available to be used. According to the First Law of Thermodynamics, energy is never destroyed during a process, it changes from one form to another. Exergy, as based on the law of increasing entropy (the Second Law of Thermodynamics), is always destroyed. Exergy analysis is important in the field of industrial ecology informing us of more efficient energy use. In 1865, Rudolf Clausius introduced a new idea into thermodynamics – *maximum useful work*, subsequently, in 1873, Josiah Willard Gibbs defined *maximum work of a chemical reaction* (Kondepudi and Prigogine, 1998).

Recently, the utilization of exergy has been widely observed not only in physics and engineering (Lior, 2008b) but also in industrial ecology, ecological economics and energetics. Exergy cost analysis is used in the evaluation of human impact on the environment. The balance between capital investment and thermodynamic efficiency must be considered together with economic competition. In any case, exergy analysis can provide useful information regarding these questions:

- does the human activity of the production of commodity A utilize more natural deposits than the production of commodity B?
- does the production of for the others commodity A use a resource's exergy more effectively than the production of commodity B?
- does technology A consume more exergy than technology B in the production of the same commodity?

Exergy consumption of natural resources is also influencing our environment and reveals the true impact of human activity.

3. Exergy calculation and exergy balance equation

According to Rant (Rant, 1957) "*the exergy of a system is the maximum amount of work* that can be obtained from it, in combination with an assumed uniform background environment with which it interacts." Exergy is the energy that is available to be used (*energie utilisable*, Gouy). A similar definition has been expressed by Marquet (1991) that the available enthalpy or exergy is the amount of work obtainable when some matter is brought to a state of equilibrium with its surroundings by means of reversible processes. An alternative definition of exergy more instrumental to the Cumulative Exergy Consumption (CExC) was formulated by Szargut (2005). "*Exergy expresses the amount of mechanical work necessary to produce material in its specified state from components common in the natural environment, in a reversible way, heat being exchanged only with the environment*". Exergy does not satisfy the law of conservation. Every real chemical or physical process is irreversible and causes non-avoidable losses of exergy (Bejan, 1995)

$$\delta B = T_o \sum \Delta S \tag{1}$$

$$\delta \dot{B} = T_o \dot{S}_{\text{gen}} \tag{2}$$

where T_o is environmental temperature, ΔS is the sum of the entropy increase of all kinds of matter occurring in the process and $\dot{S}_{\text{gen}}$ represents entropy generation rate created during all internal irreversible processes. Thermal exergy depends on the temperature, pressure and chemical composition of the matter. Its specific values, b_{th} can be divided into two parts – physical b_{ph} and chemical b_{ch} exergy (Szargut et al., 1988):

$$b_{\text{th}} = b_{\text{ph}} + b_{\text{ch}} \tag{3}$$

Specific physical exergy b_{ph} can be directly introduced from Gibbs free enthalpy:

$$b_{\text{ph}} = h_{\text{ph}} - T_o s_{\text{ph}} \tag{4}$$

where h_{ph} and s_{ph} denote the specific enthalpy and entropy, respectively.

In the case of ideal gases, physically specific exergy can easily be derived from Eq. (4) and the final result is:

$$b_{\text{ph}} = c_p \left(T - T_o - T_o \ln \frac{T}{T_o} \right) + \text{R}T_o \ln \frac{P}{P_o} \tag{5}$$

where T and P denote temperature and pressure of gas.

The value of chemical exergy, b_{ch} results from the difference in chemical composition of the substance at environmental temperature T_o and pressure P_o. The values of b_{ch} have been tabulated and can be found in databases and literature (Szargut et al., 1988; Valero, 2005).

Using exergy, several different indexes can be defined. For example:

- *thermodynamic efficiency ratio (or reversibility ratio)* (Grassmann, 1979)

$$\eta_{\text{th,eff}} = \frac{\dot{B}_-}{\dot{B}_+} \tag{6}$$

where $\dot{B}_-$ and $\dot{B}_+$ are exergy flows entering and leaving the system.

- *exergy dissipation* (Gaggioli, 1980)

$$\delta \dot{B}_{\text{diss}} = \dot{B}_+ - \dot{B}_- \tag{7}$$

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