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Fuel Part and Mineral Part of the Thermoecological Cost

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Abstract

The thermoecological cost, expressing the cumulative consumption of nonrenewable exergy per unit of the considered useful product, may be divided into the fuel part and the mineral part. The fuel part may be eliminated by the utilization of renewable exergy carriers. The mineral part cannot be eliminated. The depletion of mineral resources leads to the necessity of utilization of more and more lean natural resources. The equation system determining the fraction of the fuel part of thermoecological cost is formulated. Two numerical examples are included. The first one is a simple demonstration example. The second is detailed and relates to the Polish energy system.

Keywords*: Resources of exergy; cumulative consumption; depletion of resources.*

1. Introduction

The application of exergy in solving the optimization problems of thermal processes has been developed in the last decades in two directions. The first one called thermoeconomics aims at a maximum of economic profit, expressed in monetary units. One of the pioneers in that domain was Y. M. El-Sayed (El-Sayed, 1970a; 1970b). The second direction initiated by J. Szargut (Szargut, 1978; 1986; 1997) is based upon the concept of the thermoecological cost (TEC), expressing the cumulative exergy depletion of nonrenewable natural resources burdening the considered consumption product. The mentioned index is expressed in the units of energy-exergy, not in monetary units.

The depletion of nonrenewable natural resources is very dangerous for the future economy of humankind. The values of the TEC may be used for the selection of production technology and for the optimization of the design and operational parameters of the production installations (Szargut, 2004). The calculation of the TEC may be performed in the scope of the total globe or in the limits of some region or country. When considering only some country, the data characterizing export and import of the products and raw materials should be taken into account. The so far elaborated calculation methods take into account all the kinds of nonrenewable natural resources. However there exist a substantial difference between the fuel resources and the mineral resources. Fuel resources can be eliminated by the use of renewable natural exergy resources, for example, by the exergy of solar radiation or its secondary forms (wind, water from atmospheric falls, chemical exergy of plants). Mineral resources cannot be eliminated, because any renewable mineral resources do not exist. Therefore, the partition of the TEC into the fuel part TEC_f and the mineral part TEC_m is expedient.

2. System of balance equations

The total value of TEC of the products of every process equals to the sum of values of inflow exergy components (Stanek, 2009). Hence, the balance equations may be used for the calculation of the values of TEC. The balance equations are mutually dependent if some useful product is applied as a raw material in another production process. Only in that case a system of balance equations should be formulated. In the case of ready consumption products the balance equations are mutually independent and can be used by means of a sequence method, beginning with the product and going back through all the production steps. The balance equations may be formulated according to the principles of life cycle assessment, LCA (Cornellisen, 2000). After the wear of the production installation, its solid components can be recycled for the use in building new production installations. That fact, according to the LCA, should be taken into account in the balance equation determining the TEC. The secondary materials obtained after the wear of the production installation can be treated similarly as the useful byproducts.

The calculation of the TEC_f and TEC_m can be made in two steps. In the first one the general form of the balance equations determining the total TEC has to be formulated in the form presented in (Stanek 2009, Szargut 1986). In the second step the balance equations may be formulated that contain the unknown fractions z_j, z_i of the TEC_f in the total value of TEC. The second equation system is independent from the first one.

Every balance equation determining the TEC contains on the outflow side the specific TEC value of the major product and the values characterizing the connected useful byproducts (Szargut, 1978). When calculating the TEC values, the secondary raw materials obtained after the dismantling of the worn installation should be taken into account in the outflow components, similarly as the byproducts.

The TEC of every useful byproduct should be expressed by the value of TEC of a major product fabricated in another process and replacing the considered byproduct. The replacement ratio between the byproduct and the replaced major product should be taken into account.

On the inflow side of the balance equation the TEC values of the used domestic raw materials and semifinished products are introduced, also the TEC values of the imported raw materials and semifinished products, the immediate consumption of the nonrenewable exergy extracted from nature, the TEC of the wear of machines and installations, and the TEC of compensation of losses that are due to the rejection of deleterious waste products.

The first system of the mentioned balance equations determining the total TEC reads:

$$\rho_j + \sum_i (f_{ij} - a_{ij})\rho_i - \sum_r a_{rj}\rho_r = \sum_f b_{fj} + \sum_m b_{mj} + \sum_k p_{kj}\zeta_k \quad (1)$$

where:

ρ_j, ρ_i, ρ_r — total value of the TEC of major product of the j^{th} considered process, of the remaining processes belonging to the system and of the r^{th} imported product;

b_{fj}, b_{mj} — exergy of the fuel and of the mineral raw material immediately extracted from nature, per unit of the j^{th} major product;

a_{ij}, a_{rj} — coefficient of the consumption of the ith domestic and rth imported semi-finished product per unit of the j^{th} major product;

f_{uj} — coefficient of production of the uth byproduct per unit of the j^{th} major product;

p_{kj} — coefficient of the production of the kth rejected waste product per unit of the j^{th} major product;

ζ_k — total TEC of compensation of the deleterious impact of the k^{th} rejected waste product.

The values of ρ_j , ρ_i are unknown in the first equation system. The second system of balance equations independent from the first one determines the fuel part of TEC:

$$z_j\rho_j + \sum_i (f_{ij} - a_{ij}) z_i\rho_i - \sum_r a_{rj} z_r\rho_r = \sum_f b_{fj} + \sum_k p_{kj} z_k\zeta_k \quad (2)$$

where:

z_j , z_i , z_r , z_k — the fraction of fuel part of the considered quantity.

The values of z_j, z_i are unknown in the second equation systems. In Eqs. (1) and (2) the components with b_f, b_m appear only when considering the mines extracting raw materials from nature.

The TEC of the imported materials results from the assumption that the financial means for the import are gained by export. Hence the values of TEC of imported materials results from their monetary cost and from the mean TEC-value of the monetary unit of export:

$$\rho_r = \frac{\sum_e S_e\rho_e}{\sum_i S_e D_e} D_r = D_r\rho_m \quad (3)$$

where:

D_r, D_e — monetary cost per unit of the imported and exported product;

S_e, ρ_e — number of units of the annual export of the e^{th} product and its index of the total TEC;

ρ_m — mean value of the total TEC per monetary unit of export.

The so determined values of TEC of the imported materials should be divided into the fuel part and mineral part using the proportions appearing in the domestic production:

$$\rho_r z_r = D_r \frac{\sum_e S_e z_e\rho_e}{\sum_e S_e D_e} = D_r\rho_m z_r \quad (4)$$

where:

z_e — fraction of the fuel part of TEC of exported products.

The values of z_e, and ρ_e can be determined by means of a difficult iterative method.

When considering electricity produced from renewable resources, the fuel part and mineral part of TEC of the used operational and investment means should be taken into account.

3. Example 1

A simplified system presented in Fig. 1 is considered. The system comprises a coal mine 1, an iron ore mine 2, a power plant 3 fed with coal, steel works (with coke plant) 4, and a natural gas mine 5 extracting gas from a domestic resource. Some amount of natural gas is imported and consumed in the steelworks.

The consumption coefficients shown in Fig. 1 take into account only the time of normal operation and express:

- in the coal mine: electricity and steel products;
- in the iron ore mine: electricity and coal;
- in the power plant: hard coal;
- in the steel works: coal, iron ore, electricity, domestic natural gas and imported natural gas;
- in the mine of natural gas: electricity.

The immediate depletion b_j of domestic natural resources comprises the chemical exergy of hard coal and of natural gas (fuel part) and chemical exergy of iron ore (belonging to the mineral part).

The considered waste products are SO_2, NO_x and dust. The quantity ζ_k in Eq. (1) appears only with the consumption of coal. The assumed values of ζ_k, z_k of the mentioned waste products are $\zeta_1=\zeta_{SO2} = 108.0$; $\zeta_2=\zeta_{NOx} = 79.0$; $\zeta 3=\zeta_d = 59.0$ MJ/kg, and $z_k = 0.99$.

The value of TEC of imported natural gas results from the assumption of exported domestic products (coal and steel products in the mass proportion 4:1). The sell price of coal is 0.15 EUR/kg and of steel products 0.75 EUR/kg. The purchase price of the imported natural gas is 0.01 EUR/MJ. Application of Eqs (3) and (4) requires an iterative procedure because the production of steel is also burdened with the consumption of imported natural with the TEC depending on the consumption of coal in the steel production.

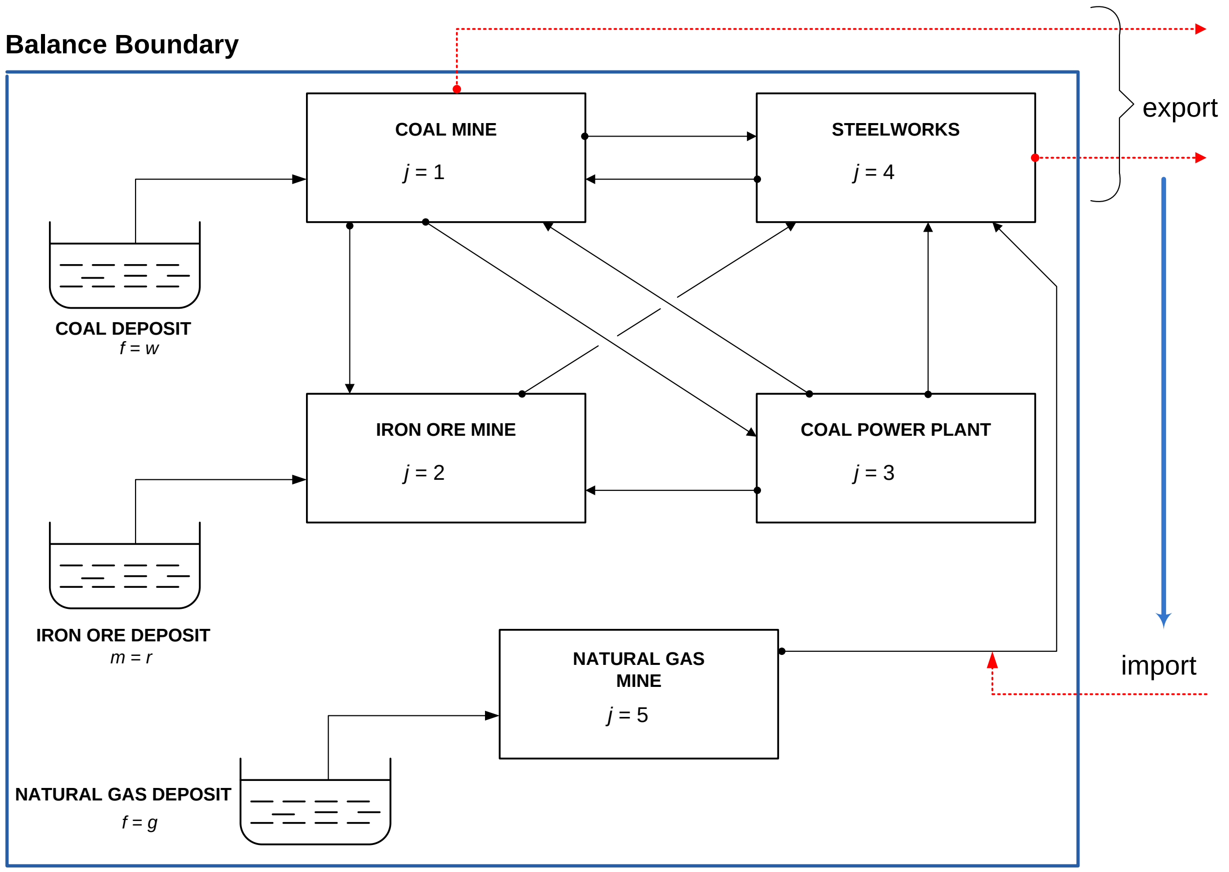

Figure 1. Simplified production system.

Table 1. Data and calculation results in the Example 1.

		Considered *j*th process				
		1	2	3	4	5
		kg	kg	MJ	kg	kmol
Consumed *i*th product a_{ij} [i]/[j]	$i = 1$	–	0.001	0.137	0.410	–
	2	–	–	–	1.340	–
	3	0.240	0.094	–	2.000	4.170
	4	0.120	–	–	–	–
	5	–	–	–	0.002	–
	5r	–	–	–	0.005	–
p_{kj} kg/[j]	$k = 1$	0.0001	0.0002	0.001	0.0004	0.0000
	2	0.0001	0.0002	0.002	0.0001	0.0000
	3	0.0001	0.0002	0.003	0.0006	0.0000
b_j MJ/[j]		26.16	0.80	0.00	0.00	809.43
ρ_j MJ/[j]		30.96	1.33	4.78	30.23	829.36
r_j		1.18	1.66	4.78		1.03
z_j %		99.49	37.82	99.54	95.81	99.99

The symbols [j], [i] denote the unit of j^{th} and i^{th} product.

The calculated values of discussed quantities are cited in Table 1. The values of the fuel part of TEC dominates in the case of all considered major products with exception of iron ore manifesting the fraction 0.6 of mineral part.

4. Example 2

Example 2 relates to the Polish energy and technology system and bases upon the data of 2008 year. The data characterizing the export are cited in Table 2.

Table 2. Structure of the Polish export in year 2008

No.	Fuel/ semi-finished products/ finished products	S_e kt	d_e mln €
1	Coke	6 118	1 701
2	Hard coal	8 500	955
3	Steel blocks	4 263	4 283
4	Cooper	436	2 058
5	Steel products	1 479	591
6	Aluminum	479	1 465
7	Machines & devices	605	4 469
8	Agricultural products - meat	1 222	2 368
9	Agricultural products - vegetable	2 863	2 553
10	Paper	1 549	1 214
11	Refinery products	2 670	1 408
12	Fertilizer	2 403	758
13	Silver	1	371
14	PCV	1 094	1 137
15	Rubber products	120	193
16	Glass	499	465
17	Wood	1 434	450
18	Sulfur	474	99
19	Cement	589	54

The high diversity of exported products compels the aggregation of similar products. The values cited in Table 2 determine the mean TEC and the mean fuel fraction of TEC per monetary unit of the sell price of exported products: ρ_m = 52.0 MJ/Euro, and z_r = 0.99. Table 3 contains the values of total TEC and of its fuel fraction characterizing the most important domestic industrial products.

Only in the case of sulfur and copper ore is the fuel fraction of TEC considerably smaller than 100%.

5. Conclusions

The partition of the TEC into a fuel part and mineral part is purposeful because the depletion of mineral resources is more dangerous for the future economy of humankind. Any renewable mineral resources do not exist. The destructed rich mineral resources may be replaced only by the more lean ones requiring a higher consumption of exergy in their utilization process. Fortunately the fraction of mineral part of the TEC is usually very small, it is remarkable only in the case of immediate products of the mines of minerals. It is worth stressing, the chemical exergy of natural fuels can be calculated with sufficient accuracy, whereas the chemical exergy of minerals can be only approximately estimated.

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Table 3. TEC of selected product

No.	Product	TEC MJ/[j]	z_j
1	Coking coal	31.20	1.000
2	Natural gas	835.86	1.000
3	Electricity	3.42	1.000
4	Coke	47.44	1.000
5	Sinter	5.95	0.997
6	Pig iron	30.46	0.999
7	Hard coal	27.08	1.000
8	Oxygen	156.41	1.000
9	Lime	8.38	0.981
10	BOF steel	27.40	0.999
11	EAF steel	12.12	0.999
12	Metallurgical products	27.16	0.999
13	Sulphur	24.60	0.223
14	Copper ore	0.97	0.382
15	Copper	169.48	0.987
16	Cement	5.91	0.959
17	Copper products	304.47	0.993
18	Machines and devices	193.77	0.999

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