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Keynote paper

Depletion of the non-renewable natural exergy resources as a measure of the ecological cost

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Abstract

The cumulative consumption of non-renewable exergy connected with the fabrication of particular products has been termed as their ecological cost. System of linear input–output equations determining the ecological costs has been formulated. The cogeneration processes have been considered using the principle of the avoided costs of fabrication of the products substituted by the by-products of the considered process. The ecological cost determined in a regional scope takes into account the ecological cost of the imported raw materials and semi-finished products. This quantities have been substituted by the economically equivalent export of own products. The deleterious effect of the rejection of waste products to the environment has been approximately determined by means of the monetary indices of harmfulness of waste products. It has been proved, that the ecological cost of human work cannot be introduced into the set of input–output equations.

Exemplary calculations have been made for the products connected with the blast-furnace process. The influence of the injection of auxiliary fuels into the blast furnace on the ecological cost of pig iron has been analyzed too.

Keywords: Exergy; Ecological cost; Natural resources; Environmental losses; Major energy carriers; Pig iron

1. Introduction

The human activity is possible thanks to the utilization of natural resources differing in their composition and/or thermal parameters from the values commonly appearing in the environment. The depletion of non-renewable natural resources is very dangerous for the future existence of the mankind. Therefore the minimization of the depletion of non-renewable natural resources should be accepted as a very important tool of the protection of natural environment [1–7]. The

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Nomenclature

a_{ij}, a_{rj}, a_{uj} coefficient of the consumption of *i*th domestic intermediate product, *r*th imported semi-finished product and *u*th by-product per unit of the *j*th major product
b specific exergy
b^* specific cumulative consumption of primary exergy
b_{sj} exergy of the *s*th non-renewable natural resource immediately consumed in the process under consideration per unit of the *j*th major product
B annual exergy consumption of non-renewable natural resources
d_{ij} auxiliary consumption coefficient, taking into account the import of semi-finished products per unit of the *j*th major product
D_i, D_r monetary value of the *i*th exported and *r*th imported product
f_{ij} coefficient of by-production expressed in units of *i*th substituted major product per unit of the *j*th major product
f_{uj} coefficient of production of *u*th by-product per unit of the *j*th major product
G_j annual production of the *j*th product
l_j coefficient of the consumption of human work per unit of the *j*th major product
m_{ij} amount of the *i*th machines or installations applied in the *j*th production process
NGP annual national gross product (e.g. $/a)
p_{kj} amount of the *k*th aggressive component of waste products rejected to the environment per unit of the *j*th major product
P_k annual production of the *k*th aggressive component of waste products rejected to the environment in the considered region
r mean ecological cost of human work, per time unit
s_{iu} substitution ratio in units of the *i*th major product substituted by a unit of the *u*th by-product
S annual ecological losses in monetary units
S_i annual export of the *i*th product
u_{ij} mean annual utilization degree of the production capacity of *i*th machine or installation in the *j*th production process
w_k monetary coefficient of ecological damages per unit of *k*th aggressive waste product
W_{d} lower calorific value
ζ_k cumulative exergy consumption of non-renewable resources due to the emission of unit of *k*th waste product
$v_{\mathrm{ng-cg(bg)}}$ ratio of substituting natural gas by coke-oven gas or blast-furnace gas
$v_{\mathrm{ec-bg}}$ ratio of substituting energy coal by the blast-furnace gas
ρ_j specific ecological cost of the *j*th product
ρ_{m} ecological cost of the exported products, per monetary unit
τ_i durability of the *i*th machine or installation operating with rated capacity (in years)

Indices
d dust
cg, ng, bg coke-oven gas, natural gas, blast-furnace gas
ec, sc energy coal, special coal

thermodynamic evaluation of the environmental losses and natural resources has been also considered e.g. in [8,9].

Exergy can be accepted as a common measure of quality of natural resources [10]. The consumption of non-renewable exergy appears not only in the final stage of the fabrication of every product but also in processes delivering semi-finished products and energy carriers to the mentioned final stage. Therefore the cumulative consumption of non-renewable exergy [1], connected with the fabrication of the considered product and appearing in all the links of economy, can be accepted as the measure of the depletion of non-renewable natural resources. This quantity has been termed as the *ecological cost* of the particular useful products [2]. The ecological cost is expressed in units of energy and exergy and its definition differs from that of economical cost, but the calculation method is very similar. Therefore the first authors analyzing the cumulative consumption of primary energy introduced the term *energy cost* [11–13]. The term *exergy cost* is not appropriate in the present considerations, because it would denote the cumulative consumption of all the kinds of primary exergy. Therefore the term *ecological cost* has been proposed.

2. Set of equations determining the ecological cost

The values of ecological cost can be determined by means of the set of linear input–output equations similar to those expressing the cumulative consumption of exergy [14] and covering, in substance, all the links of the economy. This set would be very large. However usually the formulation and solution of the mentioned set of equations can be made in steps. In the first step the equations can be formulated for most important and strongly mutually connected links of economy (e.g. production of fuels, other energy carriers, pig iron and steel). The results of the first step of calculations can be used for the calculation of ecological cost in more specialized links, not very strongly connected with the first group.

The calculation of ecological cost can be performed in a global or regional scope. In the second case the equations should contain the ecological cost of the imported goods.

Every equation relates to the major product of the considered link. Usually however except the major product, by-products appear. The useful product belongs to the by-products if it substitutes the major product of another specialized process (e.g. the electricity produced in a heat-and-power plant substitutes the electricity produced in specialized power plants). If more than one useful product do not substitute the major products of some specialized process, the production of a complex major product appears.

The input–output balance equation formulated for jth process of regional economy, has a form:

$$\rho_j + \sum_u f_{uj}\rho_u = \sum_i a_{ij}\rho_i + \sum_u a_{uj}\rho_u + \sum_r a_{rj}\rho_r + \sum_s b_{sj} + \sum_k p_{kj}\zeta_k. \quad (1)$$

The terms representing the production and consumption of the by-products can be replaced by the terms containing the ecological cost of the ith major product substituted by the uth by-product, according to the principle of avoided expenditures (the by-product should be burdened with the consumption of semi-finished products and energy carriers avoided in the substituted process thanks to the utilization of the considered by-product):

$$f_{uj} = \frac{f_{ij}}{s_{iu}}, \quad a_{uj} = \frac{a_{ij}}{s_{iu}}, \quad \rho_u = \rho_i s_{iu}. \tag{2}$$

Eq. (1) after the introduction of (2) take the form:

$$\rho_i + \sum_i (f_{ij} - a_{ij})\rho_i - \sum_r a_{rj}\rho_r = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k. \tag{3}$$

The consumption of machines and installations can be also taken into account in Eq. (3), using their consumption coefficient:

$$a_{ij} = \frac{m_{ij}}{\tau_i G_j} u_{ij}. \tag{4}$$

3. Ecological cost of the human work

The necessity to introduce the ecological cost r of human work into the calculations of the ecological costs is a most controversial question [9]. Every calculation method of the cumulative consumption of exergy or energy should fulfill a very important criterion:

The sum of the cumulative indices of energy or exergy consumption of all the final useful products used by the society should equal to the total consumption of primary energy or exergy, taken from the natural sources.

It can be checked by means of a simple example [4], whether the introduction of the human work fulfills this criterion. The simplified system (more developed in comparison with [4]) contains coal mines, the consumption sector and the industry producing final products for consumption (Fig. 1). Some part C_k of the produced coal is consumed immediately. The remaining part C_i is used in industrial processes. The consumption of industrial products in coal mines is I_c. In order to simplify the mathematical proof, the cumulative consumption of all the kinds of primary exergy

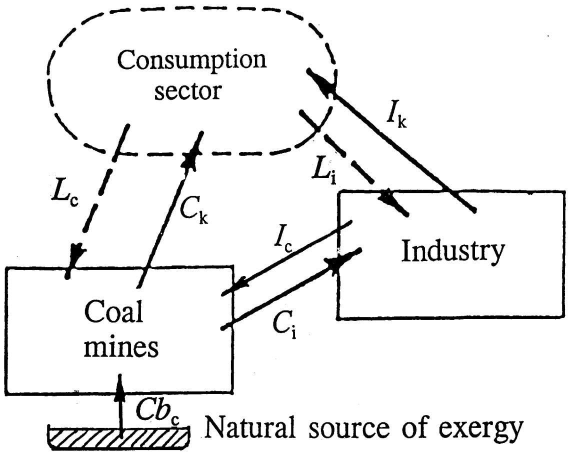

Fig. 1. Scheme of the simplified system.

has been taken into account. If we introduce the cumulative consumption of exergy burdening the human work into the balance equation (3), we obtain for the analyzed system:

$$b_c^* = b_c + (I_c/C)\rho_i + l_c r, \tag{a}$$

$$b_i^* = (C_i/I)b_c^* + l_i r, \tag{b}$$

where l_c, l_i are specific consumption of human production work in coal mines and industry, b_c is specific exergy of coal, I is amount of useful industrial products. From (b) it results:

$$b_c^* = \frac{b_c + [l_c + (I_c/C)l_i]r}{1 - (I_c/I)(C_i/C)}. \tag{c}$$

The total consumption of primary exergy can be expressed as

$$b_i^* I_k + b_c^* C_k = b_i^*(I - I_c) + b_c^*(C - C_i) = Cb_c + (L_c + L_i)r, \tag{d}$$

where

$$L_c = l_c C, \qquad L_i = l_i I. \tag{e}$$

On the other hand, we know, that the total consumption of primary exergy in the analyzed system amounts only to Cb_c. Hence, the total balance (d) of exergy consumption is closed only if the cumulative consumption of primary exergy burdening the human production labor is omitted in the set of equations determining the indices of cumulative consumption of primary exergy (or energy).

The calculation of the ecological costs is a special case of the calculation of cumulative exergy consumption, and therefore the formulated principle holds true also in this case.

4. Influence of the interregional exchange

The ecological costs of particular products differ in various regions, because of the differences in the applied technologies. The influence of interregional exchange should be taken into account when determining the indices of ecological costs in the considered region.

In Eq. (3) the ecological costs of the imported goods can be replaced by the equivalent ecological costs of the exported goods [15]. The financial means for the import are acquired by the export. Hence the mentioned equivalence can be determined only by means of the classical economical indices. It can be assumed that the ecological costs of imported goods related to a unit of monetary value is the same as that burdening the exported goods.

The index of the ecological costs of exported goods per monetary unit can be expressed as follows:

$$\rho_m = \frac{\sum_i S_i \rho_i}{\sum_i S_i D_i}. \tag{5}$$

According to the principle explained above, the ecological costs per unit of the rth imported product is

$$\rho_r = \rho_{\mathrm{m}} D_r = D_r \frac{\sum_i S_i \rho_i}{\sum_i S_i D_i}. \tag{6}$$

Hence the specific ecological costs of the rth imported product depend on unknown values ρ_i of the ecological costs of the exported domestic products.

The component representing the imported semi-finished products in Eqs. (1) or (3) can be presented as follows:

$$\sum_r a_{rj}\rho_r = \rho_{\mathrm{m}} \sum_r a_{rj} D_r = \frac{1}{\sum_i S_i D_r} \sum_i \rho_i S_i \sum_r a_{rj} D_r = \sum_i \rho_i d_{ij}, \tag{7}$$

where:

$$d_{ij} = S_i \frac{\sum_r a_{rj} D_r}{\sum_i S_i D_i}. \tag{8}$$

All the quantities appearing on the right-hand side of Eq. (8) are known. Hence the auxiliary coefficients d_{ij} are known, too, and can be introduced into the set of Eq. (3). The final form of Eq. (3) is:

$$\rho_j + \sum_i (f_{ij} - a_{ij} - d_{ij})\rho_i = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k. \tag{9}$$

The ecological cost (global or regional) can be smaller than exergy, when the considered product is burdened mainly with the consumption of renewable primary exergy (e.g. the agricultural products burdened with the consumption of renewable exergy of solar radiation or the electricity produced from renewable resources). The regional ecological cost can be smaller than exergy also in the case when the considered region (e.g. Switzerland) exports mainly the high-tech products fabricated with a small consumption of own non-renewable exergy and imports energy carriers and semi-finished products requiring a great consumption of non-renewable exergy. Hence the interregional exchange can have an essential influence on the regional ecological costs.

The number of unknown quantities ρ_i appearing in the set of Eq. (9) is equal to the number of equations. However the application of the set of Eq. (9) is not possible, if we want to perform the calculations in steps, as mentioned above, because in every of Eq. (9) appears the ecological cost of all the exported goods. Therefore an approximate method has been proposed in [15]. This method bases upon the assumption, that the structure of the export is similar to that of the domestic production. Hence the ratio of the total consumption of non-renewable exergy in the considered region to its national gross product (expressed in monetary units) can be accepted as the ecological cost per unit of the monetary value of exported goods:

$$\rho_r = D_r \frac{B}{\mathrm{NGP}}. \tag{10}$$

The calculations can be performed by the iterative method. After application of the approximate Eq. (10), the ecological cost of major semi-finished products and energy carriers can be determined, and then the values of the ecological cost of the exported goods can be corrected.

5. Approximate evaluation of the waste products

The determination of the coefficients ζ_k appearing in Eq. (9) is very difficult. Szargut formulated in [2] an exact method, which requires however to know the values of the increase of the consumption of particular final useful products due to the rejection of the unit of every waste product. The determination of the mentioned values in practically impossible. Therefore hi proposed in [6] to use the monetary indices characterizing the deleterious impact of the aggressive components of waste products:

$$\zeta_k = \frac{Bw_k}{\mathrm{NGP} + S} = \frac{Bw_k}{\mathrm{NGP} + \sum_k P_k w_k}. \tag{11}$$

The indices w_k should express the compensation costs or prevention costs of the damages due to the corrosion of buildings and industrial installations, damages in agriculture and forestry, the damages in human health too. These indices are analyzed in many publications e.g. [16]. Also these indices can be only approximately evaluated. They depend on the concentration in the environment, on the infrastructure of the country and also on the climatic zone. However only on the basis of approximately evaluated indices w_k the values of ecological cost can be determined and used for practical calculations.

It should be not reasonable to evaluate the indices w_k according to the cost of decreasing the emission of deleterious components of waste products, because the indices w_k should determine the damages appearing before the introduction of the protection methods and installation. The comparison of the costs before and after the introduction of the environmental protection should decide about the profitability of the protection. Also the assumption, that the indices w_k are proportional to the exergy of the deleterious waste products is not justified. The deleterious impact of the aggressive substances is not proportional to their exergy.

The influence of the waste products on the depletion of the resources of non-renewable exergy expressed by the ratio

$$\xi = \sum_k \frac{P_k \zeta_k}{B} \tag{12}$$

amounts to some percent. Theoretically this value could be checked by the comparison of the total ecological cost of final consumed products, calculated without taking into account the influence of waste products, with the value of B. The accuracy of calculations is however too small for this purpose.

6. Ecological cost of the products connected with the blast-furnace process

6.1. Algorithm for the calculation of the ecological cost

In order to determine the ecological cost of pig iron a group of industry branches strongly connected with the pig iron production process has been chosen. Fig. 2 presents a scheme of strong connections of the national energy system (NES) with the blast-furnace process in ironworks (IW). The group of these branches consists of: energy coal mines, special coal mines (for

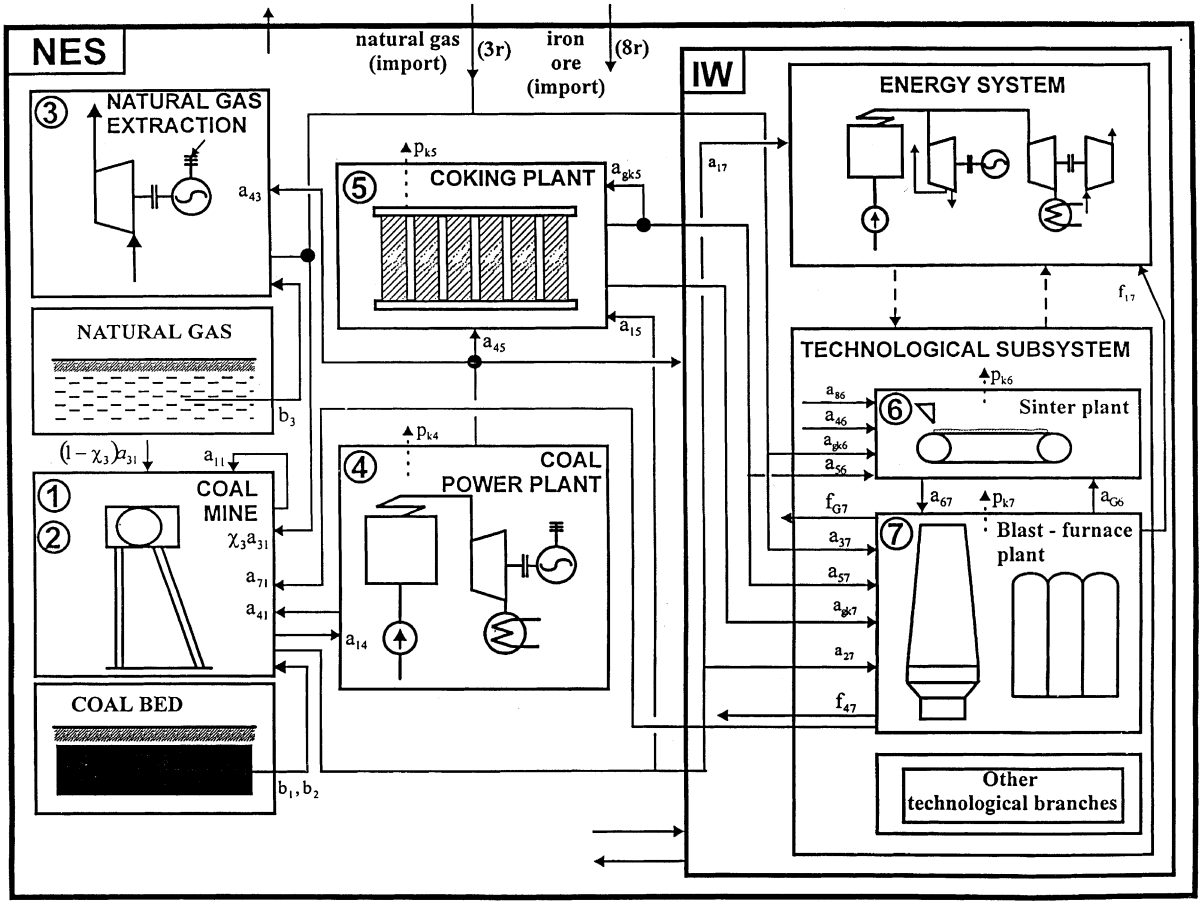

Fig. 2. Mutual connections between the processes connected with the blast-furnace process.

coke production), domestic natural gas extraction, coal power plants (dominating in Poland, especially in the considered region), coking plants, sinter plants and blast-furnace plants. Some part of the natural gas is imported. All the iron ore is imported too. For all these products the ecological cost has been calculated. It has been assumed that connections with other branches of national economy are rather weak and negligible. In order to minimize the system of ecology cost balance equations the consumption of steel is expressed by the consumption of pig iron. In this case there are two energy carriers produced as by-products (blast-furnace gas and coke-oven gas). For these fuel gases the individual ecological cost is not determined but it has also been assumed, that coke-oven gas substitutes (with the substitution energy efficiency equal to one) the imported natural gas (which closes the balance of the domestic demand), the basic production of blast-furnace gas substitutes (with an efficiency of about 0.7) the imported natural gas and the peak production of blast-furnace gas substitutes the energy coal consumed in industrial power plants. The ecological cost of imported goods related to a unit of monetary value is considered to be the same as that burdening the exported goods and the average ecological cost of exported goods is

supposed to be equal to the average ecological cost of the gross domestic product [15]. The index of the ecological cost of imported natural gas and iron ore can be calculated by means of the following formula [15,17]:

$$\rho_{3r} = D_{3r} W_{\mathrm{d\,ng}} \rho_{\mathrm{m}}, \tag{13}$$

$$\rho_{8r} = D_{8r} \rho_{\mathrm{m}}. \tag{14}$$

The ecological cost per unit of gross domestic product amounts to $\rho_{\mathrm{m}} = 34.4$ MJ/\$, the specific cost of the imported natural gas is $D_{3r} = 2.91 \times 10^{-3}$ \$/kmol, the specific cost of the imported iron ore $D_{8r} = 0.03$ \$/kg [21,22]. Thus the following results have been obtained: $\rho_{3r} = 77.1$ MJ/kmol, $\rho_{8r} = 1.03$ MJ/kg. The ecological costs of imported goods are in this case smaller than their exergy values [17]. This result can be explained by the relatively great export of agricultural products, burdened with a small consumption of own non-renewable resources.

The annual exergy consumption of domestic non-renewable natural resources in Poland contains the exergy of hard coal (hc), lignite (l), own natural gas (ng), own crude oil (co), sulphur (s) and copper ore (c). In 1995 it was:

$$B = B_{\mathrm{hc}} + B_{\mathrm{l}} + B_{\mathrm{ng}} + B_{\mathrm{co}} + B_{\mathrm{s}} + B_{\mathrm{c}} = 3315 + 579 + 145 + 22 + 47 + 15 = 4123 \ \mathrm{PJ/a}. \tag{15}$$

The index ζ_k describing the cumulative exergy consumption of non-renewable resources due to the emission of harmful substances has been defined in Eq. (11). The following data have been used in order to determine the values of ζ_k (for the year 1995 in Poland): $B = 4123$ PJ/a, NGP $= 119.8 \times 10^9$ \$/a, $w_{\mathrm{SO_2}} = w_{\mathrm{NO}_x} = 1500$ \$/Mg, $w_{\mathrm{d}} = 310$ \$/Mg, $P_{\mathrm{NO}_x} = 1120 \times 10^3$ Mg/a, $P_{\mathrm{SO_2}} = 2337 \times 10^3$ Mg/a, $P_{\mathrm{d}} = 1308 \times 10^3$ Mg/a [19,20]. Results of calculations are as follows: $\zeta_{\mathrm{SO_2}} = \zeta_{\mathrm{NO}_x} = 49.30$ MJ/kg, $\zeta_{\mathrm{d}} = 10.19$ MJ/kg.

6.2. Balance equations for the calculation of the ecological cost [21–23]

6.2.1. Production and delivery of coal (energy coal and special coal)

The consumption of the following goods has been taken into account in the case of coal mines: own consumption of coal a_{11}, natural gas a_{31}, electric energy a_{41}, steel (expressed by pig iron) a_{71} (Fig. 2):

$$(1 - a_{11})\rho_1 - \chi_3 a_{31}\rho_3 - a_{41}\rho_4 - a_{71}\rho_7 = b_1 + (1 - \chi_3) a_{31}\rho_{3r} + \sum_k p_{1k}\zeta_k, \tag{16}$$

$$(1 - a_{22})\rho_2 - \chi_3 a_{32}\rho_3 - a_{42}\rho_4 - a_{72}\rho_7 = b_2 + (1 - \chi_3) a_{32}\rho_{3r} + \sum_k p_{2k}\zeta_k. \tag{17}$$

The following coefficients have been introduced: $a_{11} = 0.0058$ kg/kg, $a_{31} = 0.000041$ kmol/kg, $a_{41} = 0.175$ MJ/kg, $a_{71} = 0.004$ kg/kg, $a_{22} = 0.0058$ kg/kg, $a_{32} = 0.000041$ kmol/kg, $a_{42} = 0.176$ MJ/kg, $a_{72} = 0.004$ kg/kg, $b_1 = 21.80$ MJ/kg, $b_2 = 30.25$ MJ/kg,

$$p_{1\mathrm{SO_2}} = p_{1\mathrm{NO}_x} = p_{1d} = p_{2\mathrm{SO_2}} = p_{2\mathrm{NO}_x} = p_{2d} = 0.0001 \ \mathrm{kg/kg}.$$

The coefficient χ_3 denotes the fraction of domestic natural gas in the total consumption (proportional to the fraction of domestic natural gas in the annual total national consumption).

6.2.2. Extraction and delivery of domestic natural gas

It has been assumed that the emission of harmful substances to the environment occurring during the extraction and transportation, as well as the own consumption of natural gas have been neglected:

$$\rho_3 - a_{43}\rho_4 = b_3, \tag{18}$$

where $a_{43} = 4.17$ MJ/kmol, $b_3 = 802$ MJ/kmol.

6.2.3. Production of electricity

Only electricity produced basing on coal-power has been taken into consideration. The average specific consumption of coal in a power plant is determined basing on the thermal efficiency of the power plant $\eta_{E\mathrm{ek}} = 0.35$

$$\rho_4 = a_{14}\rho_1 = \sum_k p_{4k}\zeta_k \tag{19}$$

where $p_{4\mathrm{SO_2}} = 0.00218$, $p_{4\mathrm{NO}_x} = 0.00101$, $p_{4d} = 0.00347$, $a_{14} = 0.124$ kg/MJ.

6.2.4. Production of coke

The consumption of the following goods is connected with the process of coke production: coal (from branch 2) a_{25}, coke-oven gas for firing the coke-oven battery a_{cg5} and 62 electric energy a_{45}

$$\rho_5 - a_{25}\rho_2 - a_{45}\rho_4 - (a_{\mathrm{cg5}} - f_{\mathrm{cg5}})\rho_{\mathrm{cg}} = \sum_k p_{5k}\zeta_k. \tag{20}$$

If we take into account the effects of substituting the natural gas by coke oven gas: $a_{\mathrm{cg5}}\rho_{\mathrm{cg}} = a_{35}\rho_{3r}$, $f_{\mathrm{cg5}}\rho_{\mathrm{cg}} = f_{35}\rho_{35}$ and $a_{35} = v_{\mathrm{ng\text{–}cg}}a_{\mathrm{cg5}}$, $f_{35} = v_{\mathrm{ng\text{–}cg}}f_{\mathrm{cg5}}$ (where $v_{\mathrm{cg\text{–}ng}} \approx 0.5$ kmol/kmol) the balance equations takes the following form:

$$\rho_5 - a_{25}\rho_2 - a_{45}\rho_4 = \sum_k p_{5k}\zeta_k + (a_{35} - f_{35})\rho_{3r}. \tag{21}$$

The following coefficients have been taken into account: $a_{25} = 1.6$ kg/kg; $a_{35} = v_{\mathrm{ng\text{–}cg}}a_{\mathrm{cg5}} = 0.00458$ kmol/kg; $f_{35} = v_{\mathrm{ng\text{–}cg}}f_{\mathrm{cg5}} = 0.0112$ kmol/kg; $a_{45} = 0.0958$ MJ/kg, $p_{5\mathrm{SO_2}} = 0.000129$, $p_{5\mathrm{NO}_x} = 0.000473$, $p_{5d} = 0.000613$ kg/kg.

6.2.5. Production of sinter

In the process of the sinter production the following goods are consumed: imported iron ore, mixed gas (coke oven and blast-furnace gas), coke and electric energy. The specific consumption of coke-oven and blast-furnace gas in the sinter plant can be expressed as the consumption of imported natural gas by means of the formula:

$$a_{36} = v_{\mathrm{ng\text{–}bg}}a_{\mathrm{bg6}} + v_{\mathrm{ng\text{–}cg}}a_{\mathrm{cg6}}, \tag{22}$$

$$\rho_6 - a_{46}\rho_4 - a_{56}\rho_5 = \sum_k p_{6k}\zeta_k + a_{86}\rho_{8r} + a_{36}\rho_{3r}. \tag{23}$$

The coefficients in Eq. (21) are: $a_{86} = 0.827$ kg/kg, $a_{36} = v_{ng-cg}a_{bg6} + v_{ng-cg}a_{cg6} = 0.0002247$ kmol/kg, (where $v_{ng-bg} \approx 0.07$ kmol/kmol) $a_{46} = 0.1073$ MJ/kg, $a_{56} = 0.0612$ kg/kg, $p_{6SO_2} = 0.003$, $p_{6NO_x} = 0.0005$, $p_{6d} = 0.006$ kg/kg.

6.2.6. Pig iron production—blast-furnace process

Pig iron is the main product of the blast-furnace process and blast-furnace gas is a by-product. The main part of blast-furnace gas substitutes natural gas, the peak part—energy coal. The blast-furnace process is connected with the production of blast, steam and oxygen. The additional consumption of energy carriers connected with these processes has been taken into account. The consumption of the following goods is connected with the blast-furnace process: energy coal, special coal (branch 2) used as auxiliary fuel, coke-oven gas, natural gas, electric energy, coke and sinter. The production of electric energy in the recovery turbine and the production of blast-furnace gas have been taken into consideration. In this case the coefficients of specific consumption and specific by-production depend on the thermal parameters of the blast and the amount of injected auxiliary fuel injection [22,24]:

$$a_{i7} = f(F, T_D, O_{2D}, p_G), \quad f_{i7} = f(F, T_D, O_{2D}, p_G), \tag{24}$$

where F is amount of auxiliary fuel, T_D is blast temperature, O_{2D} is content of oxygen in the blast, p_G is top gas pressure.

Specific consumption of energy coal for the production of compressed, enriched in oxygen and humidified blast:

$$a_{17} = D(1 + \xi_D)(a_{ecD} + O_{2D}a_{ectt} + X_D a_{ecX}), \tag{25}$$

where D is consumption of dry blast per pig iron unit, ξ_D is coefficient of blast losses in Cowper stoves, O_{2D}, X_D are consumption of technical oxygen and humidifying steam per unit of dry blast, a_{ecD} is coefficient of the consumption of energy coal for blast compression per unit of dry blast, a_{ectt} is coefficient of the consumption of energy coal per unit of oxygen, a_{ecX} is coefficient of the consumption of energy coal per unit of steam for humidification.

The specific consumption of coke oven gas (in a Cowper stove or as auxiliary fuel) is expressed as the consumption of substituted natural gas:

$$a_{37} = \left(F_{cg} + \frac{E_{Ncg}}{W_{d\,cg}}\right)v_{ng-cg}, \tag{26}$$

where F_{cg} is amount of coke-oven gas injected as auxiliary fuel kmol/Mg p.i., E_{Ncg} is specific consumption of chemical energy of coke-oven gas in the Cowper-stove.

Specific consumption of natural gas as auxiliary fuel:

$$a_{ng7} = F_{ng}, \tag{27}$$

where F_{ng} is amount of natural gas injected as auxiliary fuel kmol/Mg p.i.

The by-production of electricity f_{47} results from:

(a) the expansion of blast-furnace gas in the recovery turbine,
(b) cogeneration with the production of steam for blast humidification.

$$f_{47} = E_{\mathrm{elrt}} + D(1 + \xi_{\mathrm{D}})X_{\mathrm{D}}e_{\mathrm{el}X}, \tag{28}$$

where $e_{\mathrm{el}X}$ is the production of electricity per unit of back-pressure steam, E_{elrt} is specific production of electricity in the recovery turbine.

The part of the blast-furnace gas consumed in Cowper-stoves and in metallurgical furnaces (main part) is expressed as the consumption of substituted natural gas:

$$f_{37} = \frac{\alpha_{\mathrm{G}} E_Z v_{\mathrm{ng-bg}}}{W_{\mathrm{d\,bg}}}, \tag{29}$$

where α_{G} is share of the technological subsystem in the consumption of blast-furnace gas, E_Z is specific amount of the chemical energy of blast-furnace gas feeding the gas system of IW.

The peak part production of the blast-furnace gas (consumed in the boiler house) is expressed by the consumption of substituted energy coal of the first type:

$$f_{17} = \frac{(1 - \alpha_{\mathrm{G}}) E_Z v_{\mathrm{ec-bg}}}{W_{\mathrm{d\,bg}}}, \tag{30}$$

where $v_{\mathrm{ec-bg}} \approx 2.7$ kg/kmol.

The injected natural gas has been divided into the domestic and imported part by means of the coefficient χ_3. For example, for the thermal parameters $T_{\mathrm{D}} = 1100$ °C, $O_{2\mathrm{D}} = 24\%$, $p_{\mathrm{G}} = 0.3$ MPa, auxiliary fuel (pulverized coal)—3 GJ/Mg p.i.: $a_{27} = 0.1077$ kg/kg, $a_{17} = 0.1464$ kg/kg, $f_{17} = 0.099$ kg/kg, $a_{37} = 8.37 \times 10^{-5}$ kmol/kg, $f_{37} = 0.0017$ kmol/kg, $a_{47} = 0.0568$ MJ/kg, $f_{47} = 0.1216$ MJ/kg, $a_{57} = 0.422$ kg/kg, $a_{67} = 1.594$ kg/kg.

Balance equation of ecological cost of pig iron:

$$\begin{aligned} &\rho_7 - a_{27}\rho_2 - (a_{17} - f_{17})\rho_1 - \chi_3 a_{37}\rho_3 - (a_{47} - f_{47})\rho_4 - a_{57}\rho_5 - a_{67}\rho_6 \\ &\quad = \sum_k p_{7k}\zeta_k + (1 - \chi_3)a_{37}\rho_{3r} + (a_{37} - f_{37})\rho_{3r}. \end{aligned} \tag{31}$$

The following variants of injecting natural gas have been taken into account:

$\chi_3 = 0$—all the injected natural gas is imported,
$0 < \chi_3 < 1$—part of the natural gas is imported and the rest comes from domestic resources,
$\chi_3 = 1$—all the injected natural gas comes from domestic resources.

The coefficients of emissions of harmful substances connected with the production of pig iron are as follows: $p_{7\mathrm{SO}_2} = 0.182$ kg/Mg, $p_{7\mathrm{NO}_x} = 0.042$ kg/Mg, $p_{7d} = 0.367$ kg/Mg.

6.3. Results of exemplary calculations

Basing upon the principle of strong connections between the considered industrial branches, a simplified algorithm for calculations of the ecological cost of products connected with the blast-furnace process has been presented. This algorithm is based on the balance calculation method of the ecological cost. The results of calculations are: the ecological cost of two kinds of coal, domestic natural gas, electric energy, coke and sinter (Table 1).

Table 1
Indices of the ecological cost

Material or energy kind	Ecological cost ρ	Ratio ρ/b
Coal (type 1)	22.6 MJ/kg	1.037
Coal (type 2)	31.1 MJ/kg	1.028
Domestic natural gas	815 MJ/kmol	1.016
Imported natural gas	77.1 MJ/kmol	0.096
Electricity	3.13 MJ/MJ	3.13
Coke	49.6 MJ/kg	1.554
Sinter	4.5 MJ/kg	6.164
Pig iron[a]	32.2 MJ/kg	3.68

[a] For the thermal parameters of blast $T_D = 1100$ °C, $O_{2D} = 24\%$, pressure of the top gas $p_G = 0.3$ MPa, auxiliary fuel—pulverized coal 3 GJ/Mg p.i.

Simulated calculations of the effects of injecting auxiliary fuels on the ecological cost have been carried out for the following auxiliary fuels: pulverized coal, coke-oven gas, natural gas (Fig. 3). Generally, the injection of auxiliary fuels leads to a decrease of the ecological cost of pig iron production. The injection of imported natural gas and coke-oven gas is more advantageous than the injection of pulverized coal and domestic natural gas. The ecological analysis yields different results than energy analysis [22]. Although the injection of pulverized coal gives the best energy effects, its application is connected with a high-cumulative consumption of the non-renewable natural resources. For this reason the injection of pulverized coal is from the ecological point of view less profitable than other auxiliary fuels except natural gas from domestic resources.

Due to the interbranch connections the change of the auxiliary fuel influences not only the index of the ecological cost of pig iron, but also the indices of all the considered materials and fuels. Thus, for instance, a decrease of the index of ecological cost of the pig iron production in IW is accompanied by a reduction of the ecological costs of electricity and so on. The changes in these branches are, however, rather slight.

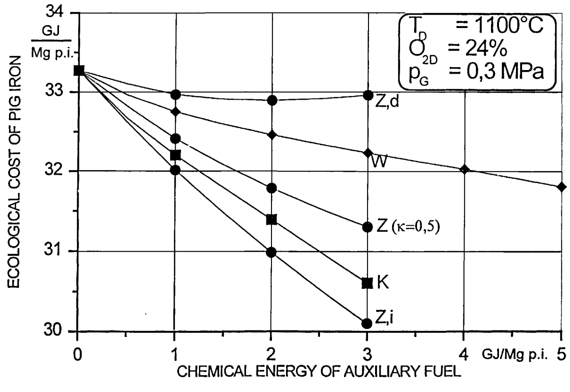

Fig. 3. Ecological cost of pig iron.

7. Final remarks

Not all the problems connected with the ecological cost have been solved as far. For example, following problems can be indicated:

1. The minimization of the ecological cost can prefer simple technologies requiring a great consumption of human work. Therefore the resources of human work can appear as a limitation in the choice of technologies.
2. Some natural resources are recoverable with delay (e.g. the wood). Also some deleterious effects of the rejection of waste products appear with delay. It is not clear, how to take into account these effects.
3. As pointed out Iantovski [25,26] it is not clear, if some kind of discount is not necessary, when minimizing the ecological cost.
4. It would be difficult to take into account the effects of the emission of CO_2, because this component of combustion gases does not evoke any immediate increase of the consumption of useful products and its monetary coefficient of ecological damages can be only conventionally assumed.
5. The global ecological cost can be used as a tool of the sustainability and life cycle analysis. E.g. according to [27] the ratio of the useful exergy to the global ecological cost should be as great as possible. Its value greater than one (thanks to the utilization of the renewable resources) should characterize a sustainable development.

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