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Energy efficiency – selected thermo-ecological problems

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Abstract The paper is devoted to some problems connected with last modification of EU directive on energy efficiency, viz.: free choice of the measure concerning the improvement of energy efficiency, i.e. final or primary energy consumption, corresponding energy savings or energy-consumption index; however without cumulative consumption or cumulative savings of primary energy. In EU directive it has been stressed the importance of measurements systems (reliable measurement information); but has not been recommended any advanced validation of measurements results, nor energy auditing or algorithms of calculating the energy savings due to improvement of energy efficiency concerning large industrial plants. Evaluation of complex buildings should be realized by means of the system method (input-output analysis). The separate problem is devoted to application of thermo-ecological approach in the analysis of complete results of improving the energy efficiency. Human activity is connected with the depletion of nonrenewable resources, including primary energy, due to not only production of consumer goods but also the necessity of compensating the unfavourable effects of harmful emissions from energy-technological processes. Therefore the index of energy-ecological efficiency has been proposed as the most competent evaluation of improvement energy efficiency of production processes and systems.

Keywords: Energy efficiency; System analysis; Exergy; Thermo-ecology; Energy-ecological efficiency

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Nomenclature

a_{ij} – direct consumption of ith product in jth branch, e.g., kg i/kg j
B – exergy
E – energy
e – index of direct unitary energy consumption
f_{ij} – by-production of ith product in jth branch
G – amount of total production
e_i – index of unitary cumulative energy consumption
m_i – estimator of ith measurement uncertainty
O_{2B} – mole fraction of oxygen in the blast
p_{kj} – specific emission of kth harmful waste product per unit of jth product, e.g., kg k/kg j
P_k – emission of the kth substance, kg k/year
t – temperature, °C
w_k – monetary index of harmfulness for the kth substance, EUR/kg k

Greek symbols

β_{sj} – direct exergy consumption of sth natural resource in jth fabrication branch, e.g. MJ/MJ or MJ/kg of jth product
$-\Delta$ – savings (decrease)
ρ_j, ρ_i – specific thermo-ecological cost of jth and ith useful product, e.g. MJ/MJ
v_i – correction of ith measurement value
ζ_k – thermo-ecological cost of kth harmful waste product, MJ/kg

Subscripts

a – avoided
B – blast
bp – by-product
ch – chemical
el – electricity
m – main product
rp – rolling product
T – total

Abbreviations

BF – blast furnace
CExC – cumulative exergy consumption
CHP – combined heat-and-power
EEE – index of energy-ecological efficiency
EUR – monetary unit, Euro
GDP – gross domestic product
PCI – pulverized coal injection
TEC – thermo-ecological cost

1 Introduction

The improvement of energy efficiency has been generally accepted as the most important factor determining the energy security. Improving the energy efficiency is also the most effective way of decreasing the depletion of non-renewable primary energy resources and for this reason the reduction of harmful emissions. The improvement of energy efficiency is realized thanks to rationalization of processes concerning the energy generation, transmission, transformation, distribution and end-use. The fundamental position in rationalization of energy use is the improvement of thermodynamic imperfection of energy processes [1]. In this matter a set of twenty practical rules have been elaborated by Professors Jan Szargut and Dominick Sama [2]. These rules should be treated as the guidelines for energy engineers. We can distinguish the following methods of rationalization, among others, improvement of exploitation of energy installations and increasing their energy efficiency, as well as utilizing the waste energy and solid wastes.

The useful tool in analysis concerning the improvement of energy efficiency is the exergy method. Its application in thermo-ecological analysis allows to evaluate the level of depletion of non-renewable resources of primary energy and finally to define the index of thermo-ecological efficiency(index of thermo-ecological cost) [3,4].

Both, Directive 2012/27/EU on energy efficiency [5] and its amendment (Directive EU 2018/2002 of the European Parliament and of the Council of 11 Dec. 2018) [6], as well as Polish Act of 20 May 2016 on energy efficiency [7] have been based on "The Energy Package" (European Commission) of 10 Jan. 2007 [8], known as "Package 3x20%", determining the following aims for the year 2020:

- reduction of CO_2 emission – 20%,
- increase of the share of renewable energy sources in energy end-use – 20%,
- savings of primary energy use – 20%.

In these documents it has been stressed that the improvement of energy efficiency is the fastest, most effective and profitable way of reducing the emissions of greenhouse gases, as well as the improving air quality and energy security. In the last version of the directive on energy efficiency (11 Dec. 2018) it has been stressed that the principle 'the energy efficiency first' should be taken into account in domestic energy policy [6].

In the year 2014 a monograph devoted to political, social and economic problems connected with improving the energy efficiency in selected EU countries, as well as USA was published in Poland [9]. Author has stressed, amongst others, a key-role of energy efficiency in improving the energy security, competitiveness and initiation of innovation. It has been stressed that the improvement of energy efficiency can be realized by better utilization of local resources of renewable energy and waste energy, as well as promotion of high efficiency cogeneration. According to information in this monograph Denmark is an example of correctly realized domestic policy of improving the energy efficiency [9]. The complexity chain of processes including energy generation, transmission, transformation, distribution, end-use as well as utilization of the wastes with recycling has been considered. The construction of high efficiency combined heat-and-power (CHP) plants belongs to the priority in Denmark. In the eighties and nineties past century the share of cogenerated heat has been increased in Denmark from 40 to 80% and share of cogenerated electricity from 20 to 50%.

This paper is devoted to some problems connected with European Union directive on energy efficiency [5,6], requiring, in authors' opinion, some comments or discussion, *viz.*:

- free choice from some options of statistical categories concerning evaluation of the value of energy efficiency,
- lack of indicating the method of advanced validation of the results of measurements,
- necessity of system approach in analysis of energy efficiency in the case of large industrial plants and complex buildings,
- depletion of non-renewable natural resources should be included not only in the direct consumption of non-renewable primary energy but also in additional consumption due to compensating the unfavourable effects of waste products (gaseous, liquid and solid).

2 Definition of energy efficiency – application of the index of cumulative non-renewable primary energy consumption

Energy efficiency can be briefly defined as 'proportion of useful effect to the consumption of energy'. Although inverse proportion determining the index of unitary direct energy consumption is more popular in practice, however, firstly it is more important to determine the conditions in which this proportion has been calculated [10]. Secondly, it should be supplemented by the method of production, design feature of technological object (among others capacity, technical level, degree of expenditure), conditions of operation and useful product [10].

Primary energy from nature both non-renewable and renewable has been transformed to final energy (direct end-use energy). Final energy is a focus of purchase by people and for this reason is the base of statistical data concerning the end-use energy consumption. Final energy is used for production of useful energy necessary for people to sustain human life and activity. The following kinds of useful energy we can distinguished: mechanical work, heat, cold, light, sound, chemical energy of food and browsing, chemical energy of materials, equipment, tools and buildings.

In the case of a single-product (one-purpose) process the index of unitary direct final energy consumption has the form

$$e = \frac{E}{G_u} \,, \tag{1}$$

where: E – total direct consumption of final energy, G_u – total production of useful product.

In the case of multiproduct (multipurpose) process, as for example cogeneration process or oxygen plant, we have two cases:

- combined process (main product and by-product substituting the main product in an avoided one-purpose process);
- coupled process (products of coupled process does not possess substituted process). In this case the contractual method of dividing input energy (e.g. exergy method) can be applied.

In the first case (combined process, e.g. CHP) the method of avoided expenditure of input energy concerning the by-products has been applied [10] and we have

$$e_{bp} = \frac{G_a}{G_{bp}} e_a \,, \tag{2}$$

where: e_{bp} – index of unitary direct energy consumption concerning the by-product, G_a – amount of avoided production in substituted one-purpose process thanks to by-production, G_{bp} – amount of by-production, e_a – index of direct unitary energy consumption concerning avoided (substituted) process.

Index of unitary direct energy consumption concerning the main product has the form

$$e_m = \frac{1}{G_m}\left(E - \sum_{bp} G_{bp} e_{bp}\right), \tag{3}$$

where: e_m – index of unitary direct energy consumption burdening the main product, G_m – amount of main production, E – total consumption of input energy burdening the combined process, bp – number of serial by-product.

In the case of coupled process division of total energy consumption between useful products is realized using adequate formula (e.g. exergy method)

$$\frac{E_i}{E} = \frac{B_i}{\sum_i B_i}, \tag{4}$$

where: E_i – input energy burdening the production of ith product of coupled process, E – total consumption of input energy burdening the coupled process, B_i – exergy of ith useful product of coupled process.

The way of improving the energy efficiency is the rationalization of production systems or processes [11]. Calculation concerning the effect of rationalization energy use should be realized by means of final energy consumption because it allows to evaluate economical effect of rationalization. But consumption of direct final energy connected with considered useful product is the incomplete consumption of energy from the point of view of domestic energy system because of connections existing in energy-technological network of production processes (first of all branches of semi-finished products and raw materials). Therefore the results of direct consumption of final energy should be converted to cumulative consumption of primary energy by means of indices of cumulative energy consumption concerning the domestic energy system [10]. In the case of non-renewable primary energy the consumption of direct final energy is always less than consumption of primary energy because in transformation processes the losses of energy are inevitable. It also should be remembered that savings of final energy not always lead to the savings of primary energy. For example the substitution of traditional heating with fossil fuels by electric heating leads to increase of primary energy due to rather low efficiency of the domestic electro-energy system [10].

So, final energy consumption does not include entire energy necessary to realize the useful effects determined by the numerator of energy efficiency definition, *viz.*, ‘output of performance, service, goods or energy’ [5], because this output is realized in a set of energy-technological networks. Energy consumption burdening every element of this output has to take place not only in the last step of these networks but also in preceding steps. The sum of energy consumption in all the steps has been called cumulative consumption of energy [10]. It can be calculated in the case of final energy (e.g. electricity) or primary energy. From the point of view of the depletion of non-renewable resources of primary energy the analysis of cumulative consumption of non renewable primary energy is the base for evaluating the improvement of energy efficiency.

Index of cumulative energy consumption of kth form of energy (e.g. primary energy of fossil fuels) is defined as

$$e*_{kj} = \frac{E_{kj}}{G_{Nj}} , \tag{5}$$

where: E_{kj} – the sum of the consumption of kth form of energy (primary or final) connecting with production of jth useful product, G_{Nj} – net-production of jth useful product.

In the case of consumption of different types of non-renewable resources of primary energy the summary index of cumulative energy consumption has been calculated from the equation

$$e*_{j} = \sum_{p} e*_{pj} , \tag{6}$$

where: $e*_{pj}$ – index of cumulative energy consumption of pth type of non-renewable primary energy concerning jth useful product, p – type of non-renewable primary energy.

The cumulative energy efficiency is defined as follows:

$$\eta*_{E} = \frac{E_u}{\sum_i G_i e*_i} , \tag{7}$$

where: E_u – useful energy, G_i – direct consumption of fuels, raw materials, semi-finished products and construction of equipments, $e*_i$ – index of cumulative energy consumption.

In the case of renewable primary energy the consumption of non-renewable primary energy is connected with its transformation into final energy (e.g. construction of hydro-electric power station).

3 Energy audit – advanced validation of measurements

3.1 System approach to analysis of energy savings

According to EU directive on energy efficiency the energy audit denotes a procedure the aim of which is to obtain the information concerning energy consumption in buildings, industrial plants, installations, services and determining the possibility of energy savings [5,6]. The base of energy audit are dedicated measurements. Directive on energy efficiency regards measurements as a very important problem. The sentences 'honest measurements data' and 'meters that accurately reflect energy consumption' can reassure about it [5,6]. But, this last sentence is not true because measurements data are burdened by some inevitable uncertainties. Therefore measurements data should be corrected by means of advanced validation procedure based on the Gauss least square method [10,12,13]

$$\sum_i m_i^{-2} v_i^2 = \min \,, \tag{8}$$

where: m_i – estimator of ith measurement uncertainty, v_i – correction of ith measurement value.

Application of this procedure is possible under condition that the measurement system is redundant [12]. The advanced method of measurements validation can be ensured by calculating the most probable results of unknown values, decreasing the uncertainty of measurement data as well as possibility of control whilst keeping the standard accuracy of measurements [10,12].

Large industrial plants and some buildings are characterized by the complexity of interconnections between production branches, particularly concerning energy carriers in which part of them are of a feedback character [14,15]. Therefore in energy analysis the system approach should be applied. From the point of view of practical applications 'input-output method' is an adequate approach in the case of implementing the directive on energy efficiency [16]. The application of input-output method allows to avoid traditional method of successive approximations concerning the solutions of energy balance equations of large industrial plant or complex buildings. The elements of inverse input-output matrix, of which significance has been stressed by the authors of [16], take into account both direct and indirect connections between energy branches, the energy balances of which are the base of input-output model of energy management concerning large industrial plants or complex buildings [14,15]. These elements, so called 'multipliers', have sense as local (inside large industrial plant or complex building) indices of cumulative energy consumption [16].

In analyses concerning the improvement of energy efficiency dominates as up to now the process approach. It means that energy savings is calculated loco energy or energy-technological process in which the project concerning the improvement of energy efficiency has been realized. If additionally the energy effect is connected with the final energy (e.g. electricity, heat, cold) delivered to considered process then the indices of cumulative energy consumption of primary energy, obligatory in domestic energy system, should be applied. It allows to calculate the savings of cumulative primary energy consumption. If, however, energy savings is a result of operating the network of energy processes with feedback loops existing in a large industrial plant or complex building, then the input-output model of energy economy of these enterprises should be applied [14,15].

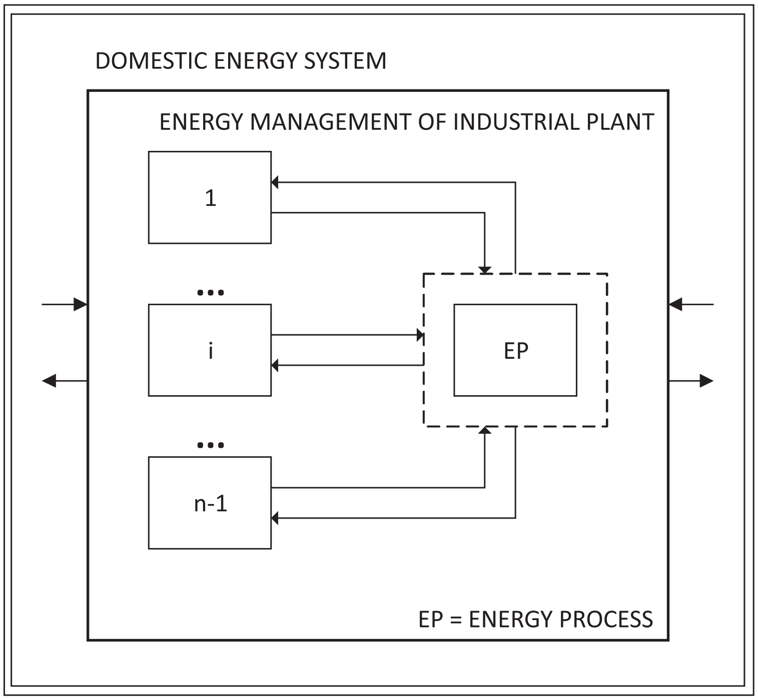

Figure 1: Connections between energy process and domestic energy system.

Figure 1 illustrates the connections between the energy process and the domestic energy system. Three balance shields have been distinguished, *viz.*, energy process, enterprise (e.g. large industrial plant or complex building) and domestic energy system. Analyzed process in which the improvement of energy efficiency is realized belongs to the network of energy and energy-technological processes. The process effects concerning a single object (energy or energy-technological process) are calculated basing on individual algorithms typical for given process. The system effects concerning given enterprise (large industrial plant or complex building) have been evaluated basing on the input-output model of its energy economy. The main matrix equation of this model has the following form [14,15]:

$$\mathbf{G} + \mathbf{F}\mathbf{G} + \mathbf{D}_G = \mathbf{A}_G\mathbf{G} + \mathbf{K}_G \,, \tag{9}$$

where: $\mathbf{G}$ – vector of the main production of energy carriers, $\mathbf{F}$ – matrix of the coefficients of the by-production of energy carriers, $\mathbf{D}_G$ – vector of supplementary supply of energy carriers, $\mathbf{A}_G$ – matrix of the coefficients of the consumption of energy carriers, $\mathbf{K}_G$ – vector of final products for technological subsystem and external consumers. From Eq. (9) vector $\mathbf{G}$ of the main production has been calculated:

$$\mathbf{G} = (\mathbf{I} - \mathbf{A}_G + \mathbf{F})^{-1}(\mathbf{K}_G - \mathbf{D}_G) \,, \tag{10}$$

where $\mathbf{I}$ denotes the unitary matrix. The elements of inverse matrix $(\mathbf{I} - \mathbf{A}_G + \mathbf{F})^{-1}$ take into account both direct and indirect connections between energy branches. These elements, as mentioned above, can be interpreted as local indices of cumulative energy consumption. They are obligatory at the balance shield of considered industrial plant [14]. These remarks also refer to complex buildings [15].

The matrix equation concerning supply of energy carriers delivered entirely from outside has the form

$$\mathbf{D}_G = \mathbf{A}_D\mathbf{G} + \mathbf{D}_T \,, \tag{11}$$

where: $\mathbf{D}_D$ – vector of energy carriers entirely supplied from outside, $\mathbf{A}_D$ – matrix of the coefficients of the consumption of energy carriers entirely supplied from outside, $\mathbf{D}_T$ – vector of energy carriers entirely supplied from outside for technological subsystem. Equations (10) and (11) describe mathematical input-output model of energy economy of industrial plant [14]. In the same way it can be created mathematical input-output model of energy economy of complex buildings [15]. Generally these input-output models are applied to close energy balances of industrial plants or complex buildings without necessity to apply traditional method of successive approximation solutions. But this is rather simple application of input-output approach. These models can be applied to system method of evaluating the effects of energy efficiency improvement. In this way not only direct connections, but also indirect connections of feedback character, have been taken into account. These system effects of improving the energy efficiency calculated on the balance shield of energy management of industrial plant can be transformed into domestic system effects by means of indices of cumulative consumption of primary energy concerning domestic energy system.

3.2 Example A — Comparison of process and system evaluation of the energy efficiency of application evaporative cooling in place of water cooling concerning metallurgical heating furnace

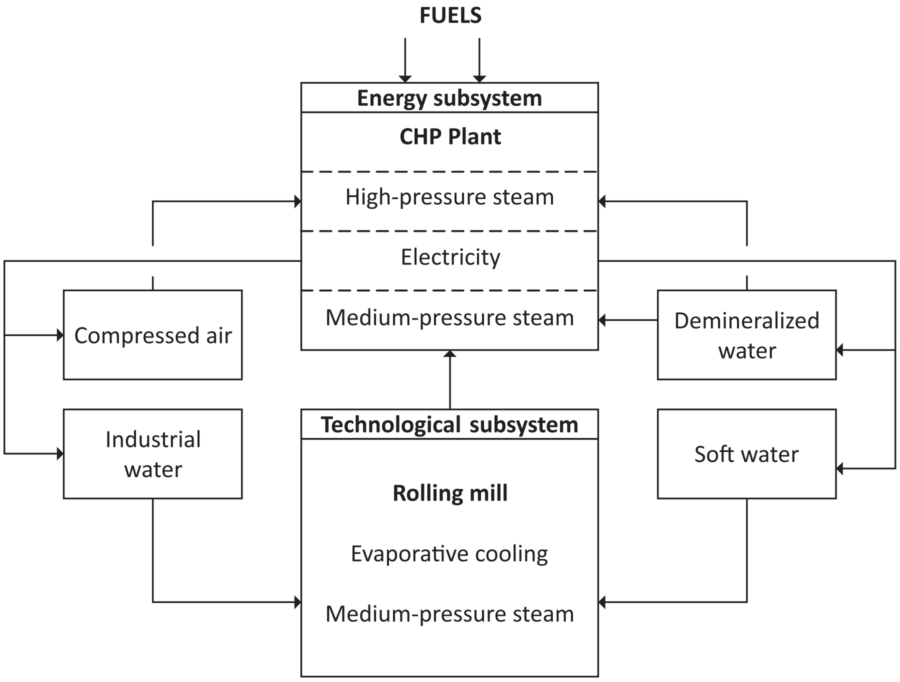

Figure 2: Direct connections between installation of evaporative cooling (technological subsystem) and part of industrial energy subsystem.

Figure 2 presents the direct connections between installation of evaporative cooling and part of industrial energy system cooling concerning metallurgical heating furnace [10,17]. Application of evaporative cooling in place of water cooling is connected with the following direct advantages:

- multiple reduction of industrial water consumption,
- by-production of useful product (medium-pressure steam),
- increasing the production and consumption of soft water.

Due to reduction of industrial water consumption the driving electricity in the industrial water pump station has been decreased but the additional consumption of soft water causes increasing the electricity consumption in soft water station. By-production of medium-pressure steam substitutes the production of medium-pressure steam in the station of pressure-reducing and attemperation of steam. As a result of this the consumption of high-pressure steam and demineralized water in this station has been reduced and in consequence consumption of electricity connected with the production of high pressure steam and demineralized water has been decreased. Decreasing the production of high-pressure steam influence first of all on reduction of the chemical energy of fuels and also electricity due to diminishing the consumption of demineralized water as well as compressed air in high-pressure steam boilers. In Tab. 1 the indices (coefficients of consumption and by-production) of direct effects of this project have been presented.

The main savings of the chemical energy of fuel $|-\Delta E_{ch}|_{mp}$ results from partial substituting the production of medium-pressure steam in the station of pressure reducing and attemperation of steam by means of by-production of the medium pressure steam in the installation of evaporative cooling:

$$|-\Delta E_{ch}|_{mp} = a_{hpmp} f_{mprp} (a_{mfhp} + a_{ffhp}) = 234\ \mathrm{MJ/Mg}\ rp\,.$$

Additionally, the reduction of internal consumption of electricity, as has been explained below, leads to further savings in the chemical energy of fuel. The reduction of direct electricity consumption due to decreasing the industrial water production, diminished by increasing the direct electricity consumption connected with increasing the production of soft water is calculated as follows:

$$|-\Delta E_{el1}| = (a'_{iw\ rp} - a''_{iwrp}) a_{el\ iw} - a_{sw\ rp} a_{el\ sw} = 0.339\ \mathrm{kWh/Mg}\ rp\,.$$

Table 1: Input data for calculating the direct effects connected with installation of evaporative cooling in place of water cooling.

Coefficients of direct consumption or by-production	Units	Before rationalization	After rationalization
Coefficient of industrial water consumption	Mg iw/Mg rp	$a'_{iwrp} = 5.658$	$a''_{iw\ rp} = 0.258$
Coefficient of soft water consumption	Mg *sw*/Mg *rp*	0	$a_{sw\ rp} = 0.098$
Coefficient of medium-pressure steam by-production	Mg *mp*/Mg *rp*	0	$f_{mp\ rp} = 0.0833$
Coefficient of electricity consumption concerning the production of industrial water	kWh/Mg *iw*	$a_{eliw} = 0.106$	
Coefficient of electricity consumption concerning the production of soft water	kWh/Mg *sw*	$a_{elsw} = 2.382$	
Coefficient of high-pressure steam consumption in the station of pressure reducing and attemperation of steam	Mg *hp*/ Mg *mp*	$a_{hpmp} = 0.837$	
Coefficient of demineralized water consumption in the station of pressure reducing and attemperation of steam	Mg dw/Mg hp	$a_{dwmp} = 0.163$	
Coefficient of electricity consumption concerning the production of high-pressure steam	kWh/Mg *hp*	$a_{elhp} = 0.986$	
Coefficient of electricity consumption concerning the production of demineralized water	kWh/Mg *dw*	$a_{eldw} = 2.382$	
Coefficient of demineralized water consumption concerning production of high-pressure steam	Mg *dw*/Mg *hp*	$a_{dwhp} = 0.4$	
Coefficient of compressed air consumption on high-pressure steam production	kmol/Mg *hp*	$a_{cahp} = 0.181$	
Coefficient of electricity consumption concerning the production of compressed air	kWh/kmol ca	$a_{elca} = 2.690$	
Coefficient of consumption of chemical energy of main fuel concerning high-pressure steam	GJ/Mg *hp*	$a_{mfhp} = 3.326$	
Coefficient of consumption of the chemical energy of fuel to fire up a boiler	GJ/Mg *hp*	$a_{ffhp} = 0.035$	

where: iw – industrial water, rp – rolling products, sw – soft water, mp – medium-pressure steam, el – electricity, hp – high-pressure steam, dw – demineralized water, ca – compressed air, mf – main fuel, ff – fire-up fuel

The decrease of direct electricity consumption connected with partial substituting the production of medium-pressure steam due to by-production of medium-pressure steam from the installation of evaporative cooling results from equation

$$|-\Delta E_{el2}| = f_{mp\ rp}(a_{hp}a_{el\ hp} + a_{dw\ mp}a_{el\ dw}) = 0.101\ \text{kWh/Mg rp}\,.$$

The diminished high-pressure steam production due to installation of evaporative cooling causes the decrease of electricity consumption because of partial reduction of the consumption of demineralized water and compressed air:

$$|-\Delta E_{el3}| = a_{hp\ mp}f_{mp\ rp}(a_{dw\ hp}a_{el\ dw} + a_{ca\ hp}a_{el\ ca}) = 0.100\ \text{kWh/Mg rp}\,.$$

The savings of electricity consumption due to evaporative cooling is as follows:

$$|-\Delta E_{el}| = |-\Delta E_{el1}| + |-\Delta E_{el2}| + |-\Delta E_{el3}| = 0.540\ \text{kWh/Mg}\,rp\,.$$

If reference efficiency of electricity production is $h_{Eelr} = 0.36$, we have

$$|-\Delta E_{ch}|_{el} = \frac{|-\Delta E_{el}|}{\eta_{E\ el\ r}} = 5.4\ \text{MJ/Mg}\,rp\,.$$

This result denotes savings of the chemical energy of fuels burdening consumption of electricity concerned with production of industrial water, soft water, demineralized water, high-pressure steam and compressed air connected with the application of evaporative cooling in place of water cooling.

Thus, the total savings of the chemical energy of fuels evaluated by means of process approach $|-\Delta E_{ch}|_{pa}$ are as follows:

$$|-\Delta E_{ch}|_{pa} = |-\Delta E_{ch}|_{el} + |-\Delta E_{ch}|_{mp} = 239.4\ \text{MJ/Mg}\,rp\,.$$

The result of total savings of the chemical energy of fuels evaluated in [10,17] by means of system approach using the input-output method [14,16] is 384 MJ/Mg *rp*. It indicates that the result of evaluating the energy savings (energy efficiency) by means of process method is lower by about 38% in comparison to the result of evaluations by means of the system method including the all interconnections between energy processes (also connections of feedback character).

4 Thermo-ecological cost as a measure of global/system energy efficiency

4.1 Theoretical part

The main idea of the system exergy analysis (cumulative exergy consumption – CExC and thermo-ecological cost – TEC) is to take into account the comprehensive system of connected processes with interactions between them. The system analysis, allows to determine the impact of individual components on the operation of the whole system, which gives a significant advantage over the local analysis of individual processes. The exergy destruction (irreversibility) in the unit separate process can influence the exergy efficiency of other connected processes (see Fig. 3). For this reason in many cases the local exergy analysis is definitely not enough, and global analysis CExC has to be applied [18–20]. It can be seen from Fig. 3 presenting the sequence of production processes that the amount of fuel exergy for the component (F) to produce the assumed product (P) is strongly dependent on exergy losses (irreversibility) of component (I). However, if the efficiency of a one single component is decreasing it induces the increased generation of exergy losses and additional induced production of other components. Finally, in the global balance boundary the economy of resources (F_T) delivered to the system will be dependent on the sequence of exergy losses in components.

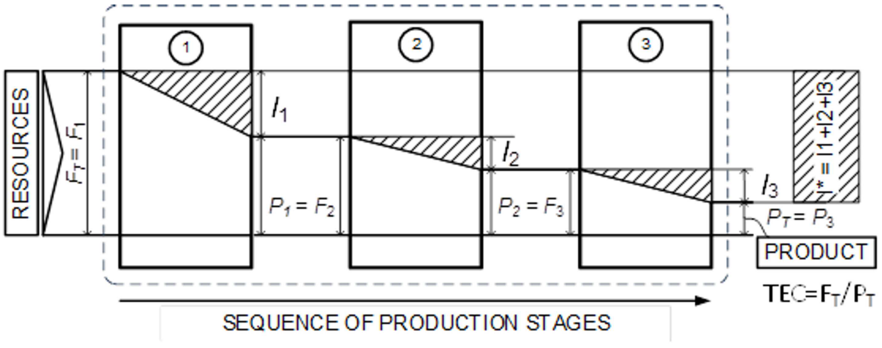

Figure 3: Sequence of production processes.

There are many practical examples which are evaluated by local and system exergy analysis that lead to quite opposite results and conclusions [18–21]. System exergy approach is especially important in the ecological application of exergy where the boundary has to reach the level of extraction of natural resources. It shows the relation to the ambient since all processes and products are linked directly or indirectly with the natural resources. The application of CExC which is thermo-ecological cost uses the exergy to assess the ecological effects, in particular, it is used to analyse the impact of human activities on the depletion of non-renewable natural resources. TEC uses exergy as a measure of natural resources quality and takes into account the whole life cycle of the product. TEC is expressed in units of exergy per unit of a product [20–23], and is defined as a cumulative consumption of non-renewable natural resources burdening this product, increased by a supplementary term accounting for the necessity to abate or compensate the negative effects of harmful wastes rejected to the natural environment [20,21,24]. The value of TEC can be calculated based on the balance of cumulative exergy consumption of non-renewable natural resources. The total value of TEC, which is represented by ρ_j, burdening the products of the jth process results mainly from the direct consumption of non-renewable exergy resources supplied to the process. Also, ρ_j results from the consumption of intermediate exergy carriers and/or materials with known TEC index. Additionally, the product of the process jth has to be burdened with the TEC resulting from rejection of harmful substances to the environment. TEC balance for jth production branch, without by-production, can be presented in the following form:

$$\rho_j = \sum_s \beta_{sj} + \sum_i a_{ij}\ \rho_i + \sum_k p_{kj}\ \zeta_k\ , \tag{12}$$

where: ρ_j, ρ_i – specific thermo-ecological cost of jth and ith useful product, e.g. MJ/MJ, β_{sj} – direct exergy consumption of sth natural resource in jth fabrication branch, e.g. MJ/MJ or MJ/kg of jth product, a_{ij} – direct consumption of ith product in jth branch e.g. kg i/kg j, p_{kj} – specific emission of kth harmful waste product per unit of jth product, kg k/kg j, ζ_k – thermo-ecological cost of kth harmful waste product, MJ/kg.

Determination of the exergy cost of compensation (TEC of harmful waste product) is one of the most complex tasks in the TEC methodology. Szargut and Stanek [21,24] proposed a simplified method to determine the TEC of harmful substances based on the information on externalities expressed by the monetary indices of harmfulness:

$$\zeta_k = \frac{B_{an}\ w_k}{\mathrm{GDP} - \sum_k P_k w_k}\ , \tag{13}$$

where: B_{an} – annual consumption of non-renewable exergy, MJ/year; w_k – monetary index of harmfulness for the kth substance, EUR/kg k; GDP – gross domestic product, EUR/year; P_k – annual emission of the kth substance, kg k/year. The cost of compensation z_k calculated from the external costs w_k for main harmful gaseous substances is presented in Tab. 2 [25].

Table 2: TEC of harmful substances.

Substance	Monetary cost w_k, EUR/kg	Thermo-ecological cost of harmful waste product, kJ/kg
SO_x	12.81	97 820
NO_x	9.41	71 880
Dust	7.00	53 420

Application of the analysis of cumulative exergy consumption as well as of the index of thermo-ecological cost can be applied to study both the energy processes [26] and large systems [27].

4.2 Example B – Application of thermo-ecological cost as a measure of the influence of metallurgical processes on the depletion of non-renewable natural resources (measure of energy-ecological efficiency)

Within this example the comparison of local and global exergy analysis of blast furnace (BF) process are presented [28–30]. The blast furnace is characterized by relatively high exergy efficiency that can reach the level of about 70%. The exergy efficiency of the whole blast furnace plant, including Cowper stoves, reaches the level of about 65%. Such high thermodynamic effectiveness of the process is possible because the counter-current flow of heat and substance is realised in the ducts of this furnace. Over 80% of consumed exergy of resources results from the consumption of coke. Improvement of resource management of blast furnace plant is aiming mainly at the reduction of coke consumption. This reduction can be achieved by means of the increase of blast parameters (temperature, pressure and oxygen enrichment of the blast) and applying auxiliary fuels. Figures 4 and 5 show the structure of the BF system (local boundary) and its connection with primary energy resources (global boundary), whereas Fig. 6 shows the percentage share of individual components of exergy balance of blast furnace plant in relation to the local boundary.

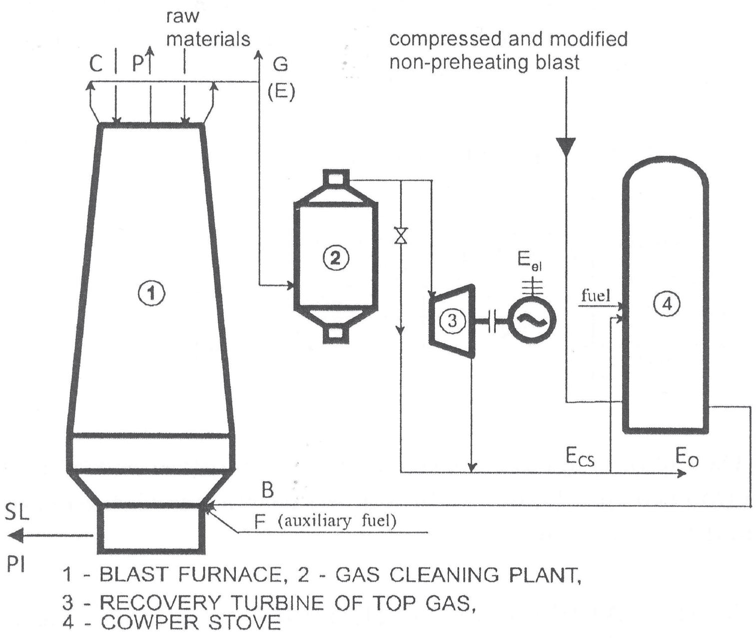

Figure 4: Structure of the blast furnace plant: B – blast, C – coke, CS – Cowper stove, D – dust, E – energy, E_{CS} – energy for CS, E_O – energy for external consumers, E_{el} – electricity, G – top gas, O – outside, P – dust, PI – pig iron, SL – slag. processes.

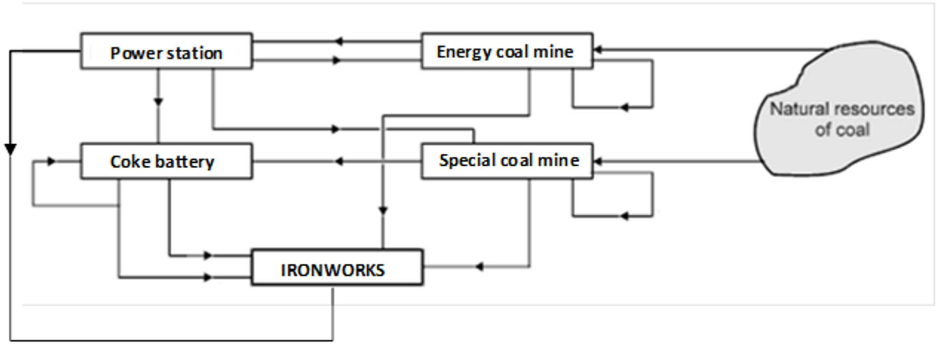

Figure 5: Connection of the blast furnace process with primary resources.

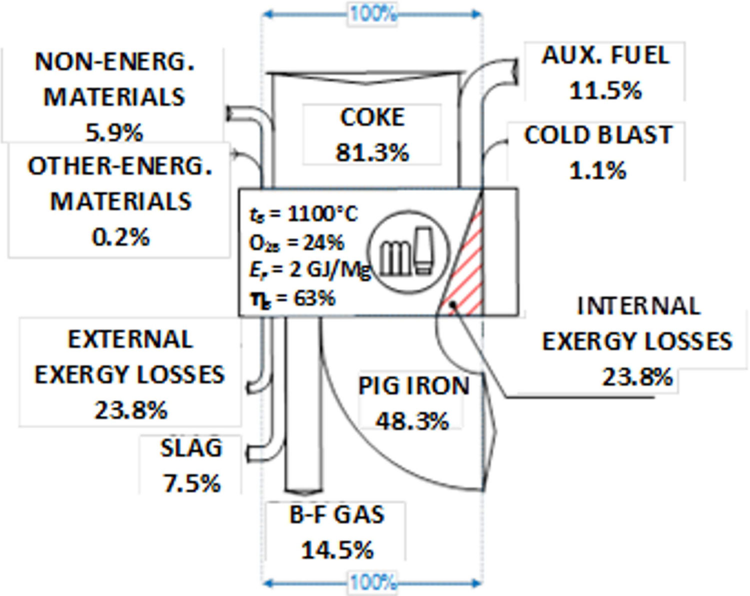

Figure 6: Percentage share of individual components of exergy balance of the blast-furnace plant.

The exergy balance of the blast-furnace plant takes the following form:

$$B_K + B_F + B_B + B_{NEC} + B_{EC} = B_{PI} + B_{BFG} + B_{SL} + \delta B_{IL} + \delta B_{EL} \ , \quad (14)$$

where: B_K – exergy of coke, B_F – exergy of auxiliary fuel, B_B – exergy of cold blast, B_{NEC} – exergy of non-energetic materials, B_{EC} – exergy of other energy carriers, B_{PI} – exergy of pig iron, B_{BFG} – exergy of blast-furnace gas, B_{SL} – chemical exergy of slag, δB_{IL} – internal exergy losses, δB_{EL} – external exergy losses.

Injection of auxiliary fuel into the blast furnace leads to disturbances in the furnace, which are visible in the decreased exergy efficiency. Injection of pulverized coal into the blast furnace influences exergy losses, which is presented in Fig. 7. Looking at the results, one may think that injection of auxiliary fuels into BF cannot be a thermodynamic improvement since it leads to exergy losses. In this case, the resource management efficiency based on the system analysis should be used. Thermo-ecological cost has to be applied (Fig. 8), to see the potential improvement related to the injection of the pulverized coal into the blast furnace process.

In Fig. 8 two cases are presented for two different blast temperatures

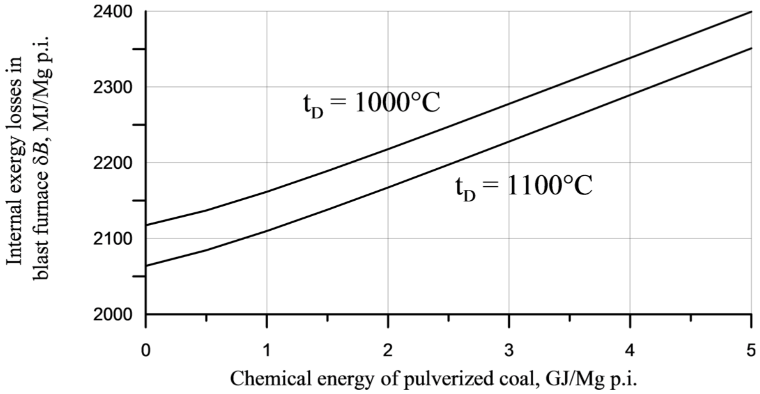

Figure 7: Exergy losses in blast furnace.

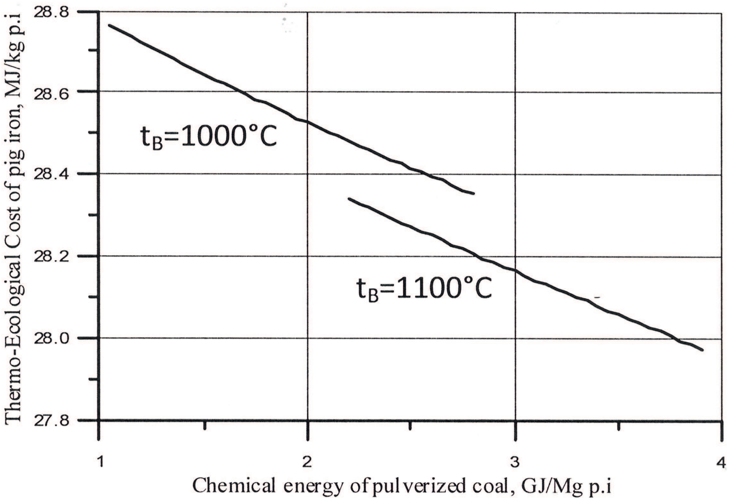

Figure 8: Thermo-ecological cost of pig iron.

equal to t_B = 1000 °C and 1100 °C for pulverized coal injection (PCI). As it was already mentioned, the opposite conclusion, when comparing results of direct exergy analysis and global exergy analysis, can be reached, namely the injection of PCI leads to the decrease of TEC and finally, to savings of primary non-renewable resources. Thus, complex energy-technology systems cannot be evaluated purely by means of local exergy efficiency or entropy generation methods [31]. Again, the presented example devoted to industrial system confirmed the importance of application of the system exergy approach in global boundary ensuring correct results and conclusions.

5 Conclusions

Energy efficiency is generally considered as the fifth technology besides carbon, gaseous, nuclear and renewable energy sources technologies. Implementation of European Union directives of 25 Oct. 2012 and of 11 Dec. 2018 on energy efficiency as well as Polish Act of 20 May 2016 concerning the energy efficiency are the most effective way towards the decrease of depletion of non-renewable primary energy resources. In consequence the emission of harmful substances has been reduced. In order to evaluate these effects the adequate measures of improving the energy efficiency index of cumulative consumption or cumulative savings of non-renewable primary energy should be applied [10,18].

The measurement systems should be equipped with advanced validation procedure based on the Gauss least square method. That ensures determination of more probable values of unknowns and decrease in the uncertainties of measurements data [10,12].

In the case of large industrial plants or complex buildings the input-output method is the adequate approach in analysis within the frame of energy audit because of feedback loops existing in energy-technological networks in these facilities [14–16].

The sum of cumulative exergy consumption of non-renewable natural resources burdening the production of useful product and additional consumption of these resources due to compensation of negative effects of harmful wastes rejected to environment, related to production of useful effect is an adequate measure not only of energy efficiency but also ecological one [22–24], the name of which could be index of energy-ecological efficiency (EEE).

The presented example devoted to the blast furnace analysis evidently showed the importance of system analysis. The injection of auxiliary fuel decreases the local exergy efficiency but in global balance boundary the effects of natural resources savings is observed. The main conclusion from this analysis is that comparing different energy or industrial technologies the boundary should be assumed at the global level of primary natural resources [10,14,28].

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