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Exergo-ecological and economic evaluation of a nuclear power plant within the whole life cycle

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ABSTRACT

The multi-criteria analysis of different power technologies takes into account TEC (thermo-ecological cost); direct and cumulative emissions; and economic evaluation. The environmental and ecological comparison of the planned nuclear power plant with the existing conventional ones (coal and gas plants) requires the evaluation of the whole life cycle of electricity generation. The main cause of the imperfection of nuclear fuel cycle appears in the stage of conversion, enrichment and nuclear fuel fabrication. TEC analysis takes into account all connected process starting from natural resources extracting, through all related processes influencing product generation, up to disposal or recycling. For this reason, TEC and exergy efficiency evaluate the nuclear fuel life cycle. TEC expresses the total (cumulative) exergy consumption of non-renewable resources burdening the analysed product, which means exergy assembly of the whole cycle of this product. TEC also takes into account the additional non-renewable exergy consumption required for environmental losses mitigation caused by the harmful emissions. A significant amount of GHG (greenhouse gasses) emissions is not covered by the direct analysis since the CO_2 emissions also occur in the stages of mining and transportation of fuel production. The nuclear power units are characterized by lower GHG emissions than the coal and gas technologies, for which the GHG emissions is on a comparable level. Additionally, the economic analysis revealed that the investment cost of the nuclear power plant is significantly higher than those of coal or gas power plant the unit cost of electricity generated by the nuclear installation could be about twice lower than from other technologies. It results from an operating cost: the cost of fuel and the fee of direct GHG emissions are higher for coal and gas technology than for nuclear power plant. The nuclear power plants seem to be the competitive technologies for the coal or gas installation and should be taken into account while planning the policy for energy generation.

1. Introduction

The global economic growth depends strongly on the power sectors, which plays a significant role in the consumption of non-renewable resources, as the electricity is one of the most important energy carriers for many industrial branches. Polish energy sector consists mainly of coal combustion plants that imply the growth of CO_2 emission. At the same time, European trends toward sustainable development and global warming mitigation may lead to significant changes in the Polish structure of electricity generation. According to the domestic energy policy, the first Polish nuclear power plant (3×1.6 GW_{el}) and an increasing number of plants based on renewable resources are planned in the perspective of the year 2030.

The environmental and ecological comparison of the planned nuclear power plant with the existing conventional ones (coal and gas plants) requires the evaluation of the whole life cycle of electricity generation. In this paper, the multi-criteria analysis of different power technologies, which include various cases of nuclear resources treating, consist of three criteria: TEC (thermo-ecological cost); direct and cumulative emissions; and economic evaluation.

The nuclear power chain is low efficient in comparison with other power technologies fed with non-renewable primary energy [1,2], taking into account the whole cycle of resources management. The identified resources of uranium, which could be extracted at

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the economic profitability, are equal to 5.47 million tons [2,3], which represents a total exergy of about $0.44 \cdot 10^{12}$ TJ. The lifetime of identified uranium resources may last for about 800 years, to maintain the total capacity of the nuclear power plant at the current level.

It is predicted that besides the identified resources of uranium the unconventional and ocean resources of nuclear energy will be used [3]. The total amount of nuclear resources could reach the level of $3 \cdot 10^{14}$ TJ, which consequently could ensure the enormous long lifetime (*R*/*P*), which is characterized by the resources (R) and production (P). In case of nuclear plants, *(R/P)* ratio refers to uranium resources (R) and fuel production (P) [2–4].

In the case of natural gas and oil, the lifetime (*R*/*P*) is significantly limited and is equal to 56 and 53 years, respectively [4]. During the last decade, in the case of coal an extremely rapid decrease of *R*/*P* ratio has been observed. The ratio *R*/*P* for coal in the year 2000 was estimated at the level of 220 years. Whereas in the year 2012, it was estimated only at the level of 109 years. In the face of these facts, it is probable that the power sector will have to use more nuclear resources.

The energy and exergy efficiencies of PWR (Pressurized Water Reactor) cycle was presented in details in Ref. [5]. The exergy and economic analysis of the components of the power system loop of PWR with fossil-fuel superheater were presented [6,7]. The exergy losses in this combined plant were significant for the turbine and superheater. However, it was only the direct analysis, not the cumulative one. It should be pointed out that direct energy and exergy efficiency of a nuclear plant are broadly discussed. Comprehensive economic analysis of new generation nuclear plant of are presented in Ref. [8]. The local economic effects and zone influence of the nuclear power plant show another important issues [9], however, it is also limited to only a few aspects. It is very important to develop the multi-criteria analysis to present the results that give the broader perspective. For this reason in the presented paper, the TEC analysis with a connection to economic and GHG (greenhouse gasses) emissions criterion are presented. The presented analysis is calculated in the full life cycle which finally gives the cumulative exergy efficiency.

2. Characteristic of the analysed systems

Power technologies are often characterized only by local energy efficiency. In the case of conventional power plants fired with fossil fuels, local energy efficiency is expressed as the ratio of the electricity generation and the chemical energy of the fuel consumption. In general, the fuel consumption and, furthermore, ecological effects (as the emissions of wastes are dependent on fuel consumption) are calculated from the previously defined local efficiency. In the case of nuclear power plants, the thermal efficiency is used as the evaluation efficiency criterion. The thermal efficiency is defined as the ratio of generated electricity and the heat delivered from reactor to the turbine cycle. Both mentioned evaluation criterions are constrained to the final component (power plant) neglecting the whole cycle leading from resources extraction to the electricity generation.

The above described energetic evaluation does not take into account the quality of resources. Moreover, in some cases (e.g. in the nuclear cycle) the destruction of resources dominates in the chain of processes of fuel extraction, processing and delivery [13,20]. For this reason, it is necessary to apply the full LCA (life cycle analysis) with the exergetic evaluation of resource quality to compare different energy technologies.

Additionally, the ecological effects have to be evaluated within the whole chain. As the starting point for such evaluation for power technologies is the assumption on the energy or exergy efficiency of the final stage – electricity generation – within the chapter the energy and exergy characteristics of the analysed technologies are presented.

Average net energy efficiency of coal power plant (PC) has been assumed at the level $\eta_{E,PC} = 40\%$. It corresponds to the average efficiency of electricity generation in the Polish energy system [11]. Energy efficiency of the BAT (best available technology) of steam power plant fired by PC (pulverized coal) is approaching the level of 50%. The net energy efficiency of BAT (best available technology) of combined gas and steam power plants (NGCC(Natural Gas Combined Cycle)) fired with natural gas is reaching now the level of $\eta_{E,CC} = 60\%$. Assuming the level of energy efficiency the exergy efficiency of the above power plants can be simply calculated as following:

$$\eta_{B,\mathrm{el}} = \frac{1}{\alpha}\eta_{E,\mathrm{el}} \tag{1}$$

where α denotes ratio of standard chemical exergy to lower heating value (after [24]: $\alpha=$ 1.09 for coal; 1.17 for lignite and 1.04 for natural gas).

The knowledge of the thermal efficiency η_{th} of the nuclear power plant is far not enough to compare with other power plants because characterise only a part of the process of electricity generation. The balance boundary of the nuclear power plant, similarly as in the case of coal and natural gas ones, has to be assumed at the level of fuel delivery to the nuclear reactor. It can be made applying the so-called *burn-up ratio coefficient* W_F, expressed usually in GWd/tU and calculated as a thermal output of the reactor Q_{th} related to mass of nuclear fuel delivered to the reactor m_F [12]. Combining the thermal efficiency of the nuclear plant defined as $\eta_{\mathrm{th}} = N_{\mathrm{el}}/Q_{th}$ and the burn-up ratio W_F the exergy efficiency of nuclear power plant can be calculated as following [1]:

$$\eta_{B,\mathrm{el}} = \eta_{th}\frac{W_F}{b_{nu}} \tag{2}$$

According to [13] it can be assumed that the average existing nuclear power plants are characterized by thermal efficiency $\eta_{th} = 31{,}6\%$ and burnout ratio [25] $W_F = 30.4$ GWd/t. For the generation III + nuclear power plants it can be assumed that [13] $\eta_{th} = 33{,}9\%$ and burnout ratio [25] $W_F = 49.6$ GWd/t. Basing on the presented characteristics of compared power plants the exergy efficiency has been calculated. Results of these calculations are summarised in Table 1.

Among considered power technologies natural gas NGCC plant is characterised by the highest exergy efficiency. The existing nuclear technologies are characterised by lower of about 10 percent point exergy efficiency than that assumed for coal technology. However, it should be taken into account that in the case of nuclear power plant the local exergy efficiency calculated within the boundary of the plant is not a deciding factor on resource depletion or CO_2 emissions because of relatively high exergy losses in fuel fabrication chain [1,20] or because of combustion process absence.

Table 1
Exergy efficiency of compared power technologies.

Power plant	Exergy efficiency $\eta_{B,\mathrm{el}}$, %
Nuclear existing	24.1[a]
Nuclear Gen III +	41.3[a]
Coal average in Poland	36.7
Coal BAT	45.9
NGCC (BAT)	57.7

PWR (66%) and BWR (Boiling Water Reactor) (34%) [13].
[a] average value for reactors existing in 2009.

For this reason to evaluate the influence of the process on the resources depletion, it is necessary to consider the full life cycle *from cradle to grave* [14–16] by means of TEC (Thermo-Ecological Cost) [1]. Moreover, CO_2 emissions have to be also compared from the point of view of full cycle using the concept of cumulative emissions of CO_2. In the case of power plants fired with fossil fuels the share of the primary energy consumption in the total life cycle resource consumption is dominant. Due to [17] and [18] this share in the case PC and NGCC is about 97%. For these reasons, the construction material part of life cycle of coal and natural gas power plant has been simplified to the major materials, as presented in Table 2. The construction material requirements taken into account in the presented analysis of nuclear power plant is presented in Ref. [20].

Analysis of the TEC (thermo-ecological cost) and cumulative GHG (greenhouse gasses) emissions for assumed nuclear power technologies has been carried out taking into account the following stages *from cradle to grave*: 1) Mining and milling of uranium ore (open pit and underground), 2) Conversion of U_3O_8 into UF_6 for the enrichment process, 3) Enrichment of nuclear fuel (centrifuge and diffusion), 4) Fuel fabrication in the form of UO_2, 5) Fuel transportation, 6) Power generation, 7) Depleted fuel management. The detailed scheme of this cycle is presented in Fig. 1.

3. TEC (Thermo-ecological cost) analysis

The physical cost of any product should take into account the total consumption of natural resources at the level of its extraction from nature. Moreover it has to be calculated using the common measure of resources quality. Such cost can be expressed by the TEC (thermo-ecological cost index) that is mainly affected by the consumption of exergy of non-renewable resources extracted directly from the nature, such as fuels, mineral ores, nuclear ores or fresh water [14,19]. TEC has been defined by Szargut [14] as: *the cumulative consumption of non-renewable exergy connected with the fabrication of a particular product with additional inclusion of the consumption resulting from the necessity of compensating the environmental losses caused by the rejection of harmful waste substances to the environment*. Consumption of resources taken into account within TEC analyses first of all appears in the production processes directly connected with the extraction of substances from the natural deposits, e.g. in the coal mine or uranium mine. However, even if not all branches of economy are directly connected to the nature due to the existing interconnections between production processes and systems each product is directly or indirectly linked to the natural resources. Then TEC is also generated by the consumption of semi-finished products exchanged between the branches of the system. In some branches, a by-production can appear which entails that the by-products replace main products in other branches and, therefore, the value of TEC of a considered main product is reduced. TEC of useful by-products should be determined by means of the avoided consumption of non-renewable exergy [14]. The balance of TEC includes also an additional consumption of resources necessary to compensate or to avoid the losses caused by the rejection of harmful wastes to the natural environment. The specific consumption of i-th useful product in j-th branch is dependent on the exergy losses or exergetic efficiency of the production component. For this reason, CEx (the exergy cost) is based purely on physical laws and its formation depending on the irreversibility of interconnected production processes. The concept of exergetic cost formation is presented in Fig. 2. The total resources input (R) depends not only on single irreversibility (I) but on the cumulation of irreversibility (I_T) through the production chain. Increase of irreversibility in single component influences the resources demand in all preceding links of the production chain.

Table 2
Plant construction material requirements, (kg/MW plant capacity) [17], [18].

No.	Construction material	Coal	Natural gas
1.	Concrete	158,758	97,749
2.	Steel	50,721	31,030
3.	Aluminium	419	204
4.	Iron	619	408

Considering the scheme presented in Fig. 2 the unit exergy cost of i-th component is defined as:

$$k_i^* = \frac{B_i^*}{B_i} = \frac{R}{P_i} = 1 + \frac{\Sigma I_i}{P_i} \tag{3}$$

TEC index is calculated basing on the similar idea as depicted in Fig. 2. The index of operational TEC can be determined by solving the set of exergy cost balance equations. The equations are formulated using the scheme presented in Fig. 3.

According to the scheme of TEC balance presented in Fig. 3 the equation for calculation of the operational TEC [14,19] takes the following form:

$$\rho_j + \sum_i \left(f_{ij} - a_{ij}\right)\rho_i = \sum_s b_{sj}^{ch} + \sum_s b_{sj}^{nu} + \sum_k p_{kj}\zeta_k \tag{4}$$

The TEC of given primary non-renewable resources in the nature is equal to its specific exergy $(\text{TEC})_{\text{prim}} = b_s$ [1,19]. In the case of nuclear resources, the specific exergy b_s in the TEC balance (Fig. 3) should in general include not only the chemical exergy of natural resources b_{sj}^{ch} but also the nuclear exergy b_{sj}^{nu}. The chemical exergy per mole of solution under normal thermodynamic parameters can be calculated from the following formula [24]:

$$(Mb)_{\text{ch}} = \sum_i z_i (Mb)_{ch,i} + (MR)T_0 \sum_i z_i ln z_i \tag{5}$$

The specific exergy of fissile nuclide carrier per its mass unit (e.g. per kg of uranium ore) is calculated using the following formula:

$$b_{\text{nu}} = g_r g_{\text{fis}} b_{\text{nuclide}} = g_U g_{\text{U235}} b_{\text{nuclide}} \tag{6}$$

where: g_r – mass fraction of radioactive element in the ore, g_{fis} – mass fraction of fissile nuclide in radioactive element.

Exergy of nuclide appearing in the Eq. (6) per mass unit of the nuclide can be calculated from the formula:

$$b_{\text{nuclide}} = \frac{N_A}{M_{\text{nu}}} b_{\text{fis}} \tag{7}$$

where: N_A – Avogadro number, M_{nu} – molar mass of nuclide.

Values of energy and exergy of fission and of nuclide are included in Table 3.

The nuclear chain from uranium ore mine to end-use of electricity from a power plant is more complicated than the chain in the case of conventional power plants. For this reason, the TEC evaluation should also fulfil the requirements of Life Cycle Analysis [13]. The TELCA (Thermo Ecological Life Cycle Assessment) based on methodology, described in the previous section has to comprise the following phases: 1) Construction Phase, 2) Operational phase and 3) Decommissioning phase of plant, in order to include in the analysis all components presented in Fig. 1. The general form of the equation to calculate the thermo-ecological cost in the whole life cycle has been formulated by Szargut [23,24]. This approach is applied to investigate the exergetic life cycle of different technologies [22]. The proposed function, expressing the yearly thermo-ecological cost has the following form:

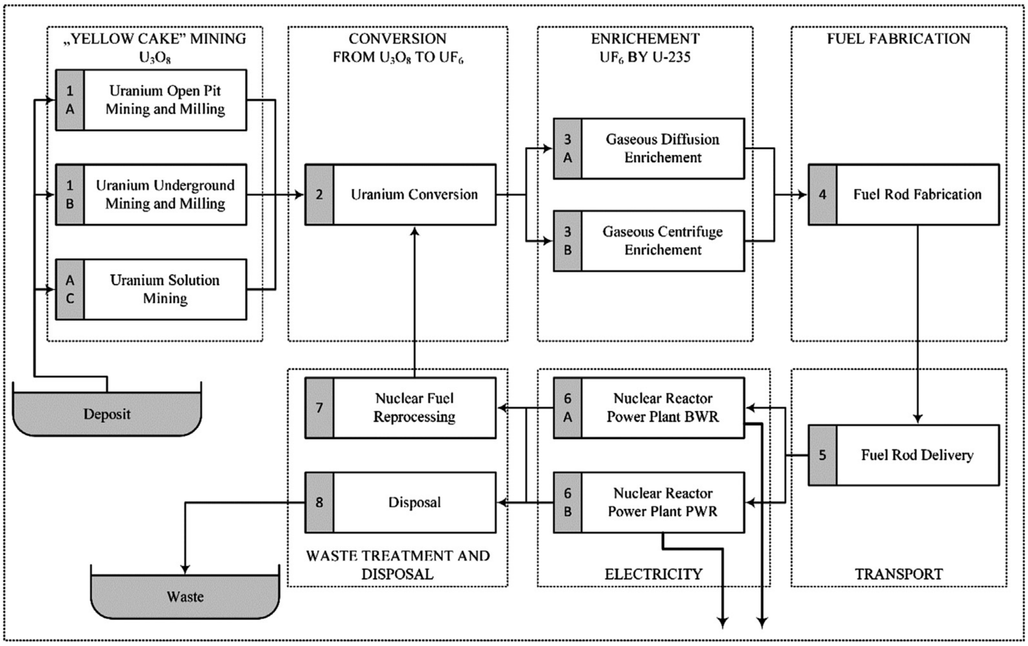

Fig. 1. The whole cycle of nuclear technology.

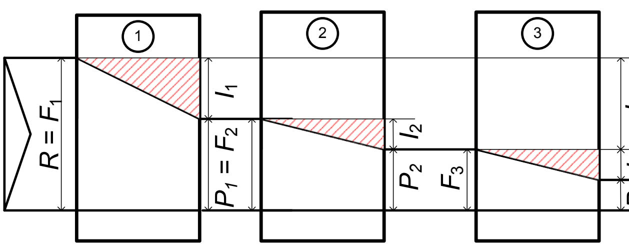

Fig. 2. Exergetic cost formation.

$$
\begin{aligned}
(TEC)_{LCA} = {} & \tau_n \left(\sum_i \dot{G}_i \rho_i + \sum_k \dot{P}_k \zeta_k - \sum_u \dot{G}_u \varrho_i s_{iu} \right) \\
& + \frac{1}{\tau} \left(\sum_m G_m \rho_m (1 - u_m) + \sum_r G_r \rho_r \right)
\end{aligned} \tag{8}
$$

The calculation of TEC has been done for all the nuclear chain presented in Fig. 1 from uranium mine to the nuclear power plant. The indices of TEC of raw material, semi-finished product or energy carrier supplied to the particular production process in the nuclear

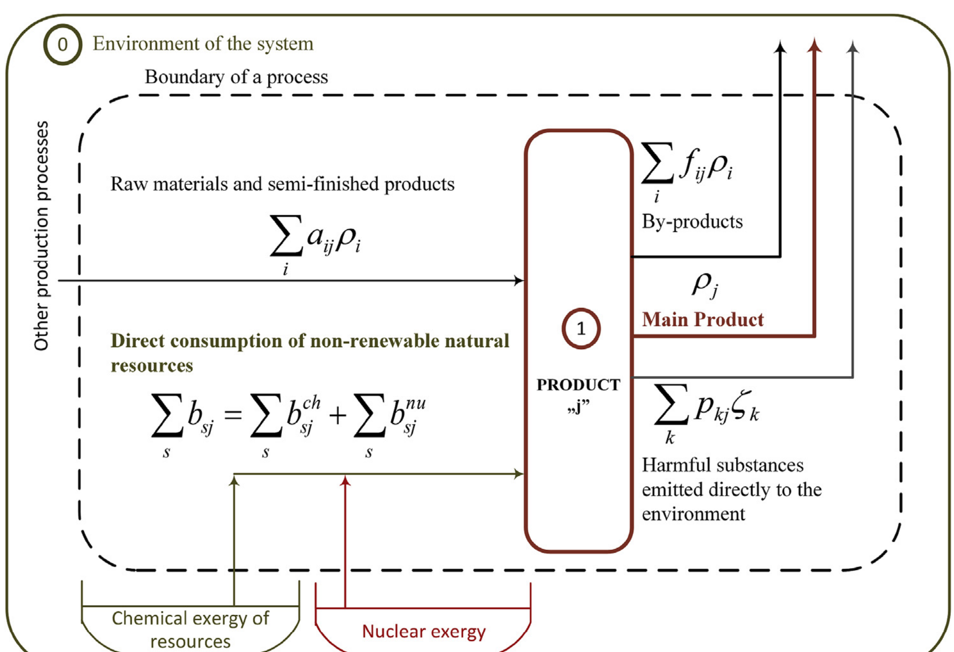

Fig. 3. Idea of TEC balance methodology.

Table 3
Energy and exergy of fission and of nuclide.

Nuclide	Fission energy, e_{fis}	Fission exergy, b_{fis}	Exergy of nuclide, $b_{nuclide}$
	MeV	MeV	MJ/kg
U233	200.0	190.0	$77.016 \cdot 10^6$
U235	203.0	192.9	$78.172 \cdot 10^6$
U238	208.9	198.5	$80.444 \cdot 10^6$
Th232	200.0	190.0	$79.018 \cdot 10^6$
Pu239	208.9	198.5	$78.475 \cdot 10^6$
Pu241	210.8	200.3	$79.189 \cdot 10^6$

chain have been determined independently on the TEC balance set formulated for the nuclear chain. Results of the TEC analysis of the whole nuclear chain from uranium mine (cradle) throughout fuel fabrication and transportation are presented in Table 4. Conversion and fuel fabrication are characterised by the highest exergy losses mainly influencing the formation of the exergetic cost of the total production chain. These processes are characterised by the following local exergy efficiencies: conversion – 28.4% and fuel fabrication – 38.1%. Also, the process of fuel enrichment is a resource consuming as its local exergy efficiency amounts to: centrifuge enrichment – 66.4% and diffusion enrichment 68.0%. It should be stressed, that in the process of exergetic cost formation the transformations of nuclear carriers and its nuclear exergy plays the dominant role. The share of nuclear exergy in the total TEC, which means in the following stages: mining, conversion and enrichment, is over 98%. It means that the consumption of other materials and energy carriers in the life cycle TEC calculation play a marginal role when the uranium ore is treated as a non-renewable resource.

Using the indices of TEC for the whole nuclear cycle (Table 4), the TEC of electricity generated in nuclear power plant has been determined. Average existing nuclear power plant (69 PWR (66%) and 35 BWR (34%)) and average nuclear power plant of generation III + have been examined. The results of the calculations are compared in Table 5.

It can be concluded, that in the case of the existing nuclear power plants the local exergy efficiency is lower at about 8% points than that in the case of average coal power plant in Poland. The recycling of spent fuel increases the local exergy efficiency at about three percent point. Nuclear power plant of generation III + can achieve the local exergy efficiency of about 41.3%, which is higher than in the case of the existing in Poland coal power plant at about 10 percent point. The recycling can further improve the efficiency reaching the level of 46.2%. However, due to the extremely high exergy losses in the nuclear chain from mine to the fuel fabrication process, the system exergy efficiency of the whole nuclear power plant cycle is very low. In the case of the existing technology, it is about 1.7%, in the considered generation III + about 2.9%. It is about 10 times lower than the system exergy efficiency of the existing

Table 4
Results of TEC analysis of fuel chain uranium mine – power plant.

Stage	Product	Exergy of product b_P GJ/kg	Specific TEC ρ_P MJ/MJ
Mining (open pit mine)	U_3O_8, yellowcake	464.03	1.006
Mining (underground)	U_3O_8, yellowcake	464.03	1.017
Conversion	UF_6 (0.7%)	370.01	3.568
Enrichment (centrifuge)	UF_6 (5.0%)	2642.91	5.370
Enrichment (diffusion)	UF_6 (5.0%)	2642.91	5.247
Fuel fabrication + transport	UO_2 (5.0%)	3445.41	14.089

Table 5
Results of TEC analysis of nuclear power plant.

Power plant	Local exergy efficiency $\eta_{B,el}$, %	$(TEC)_{LCA}$ MJ^a/MJ_{el}	System exergy efficiency $\eta^a_{B,el}$, %
Nuclear existing	24.1	58.39	1.71
Nuclear Gen III +	41.3	34.13	2.93
Nuclear existing (recycling)	27.0	57.80	1.73
Nuclear GEN III + (recycling)	46.2	33.78	2.96
Coal average in Poland	31.8	3.90	25.64
Coal BAT	45.9	2.64	38.90
BAT NGCC	57.7	1.82	54.34

[a] Cumulative.

coal power plant that amounts to 25.6%. Processes of fuel preparation especially conversion and enrichment have the dominant influence on the high exergetic cost of the whole nuclear chain. The structure of TEC can be investigated decomposing the total cost proportionally to irreversibilities burdening the particular steps from mine to fuel fabrication. Taking into account that the share of nuclear exergy in the total TEC, is over 98% the cost can be decomposed simply due to concept presented in Fig. 2 using the formula given by Eq. (3). The analysis of the influence of particular components of fuel preparation chain on the total TEC of nuclear fuel has been carried out for four chains presented in Fig. 4.

The results of calculations for the degree of enrichment at $g_{U\text{-}235} = 5\%$ are presented in Fig. 5.

It can be concluded that the TEC of nuclear fuel is mostly influenced by the process of the enrichment. In the case of gas centrifuge enrichment the consumption of natural uranium per unit of enriched uranium is amounting to 10.75 kg/kg while in the case of gas diffusion enrichment the same factor is amounting to 10.40 kg/kg. The influence of the fuel enrichment on total cost is about 9% while the contribution of fuel fabrication is amounting to about 12%. The process of uranium ore mining has relatively low input to total TEC amounting to about 0.6% for open mine and to about 1.7% in the option with the underground mining. The next important factor deciding on the total TEC of nuclear fuel delivered to the power plant is the degree of enrichment. In Fig. 6 the influence of enrichment degree on the TEC of nuclear fuel are presented for the range of the degree of enrichment between 3 and 5%.

Between the degree of enrichment at 3% and 5% the changes of TEC are significant and have been estimated as 6 MJ/MJ.

4. Cumulative GHG (CO_{2e}) emissions

The anthropogenic CO_2 emission is closely related with the energy efficiency of the transformation of primary fuels, and carbon element content in fuel. Direct emission of carbon dioxide resulting from carbon-containing fuel per unit of chemical energy can be evaluated from the formula:

$$\varepsilon_F = \frac{c}{12} \frac{M_{CO2}}{(LHV)} \tag{9}$$

However, the process of mining, processing and delivery of fuel can be also burdened with significant GHG emissions. For example, there appear methane emission from coal mines or leakages from natural gas transportation pipelines. Inclusion of these impacts can radically change the picture. For this reason, to complete evaluation of different energy sources on GHG emissions a cumulative calculus has to be applied. Such balance in the case of GHG (greenhouse gasses) emissions takes the following form [15,21]:

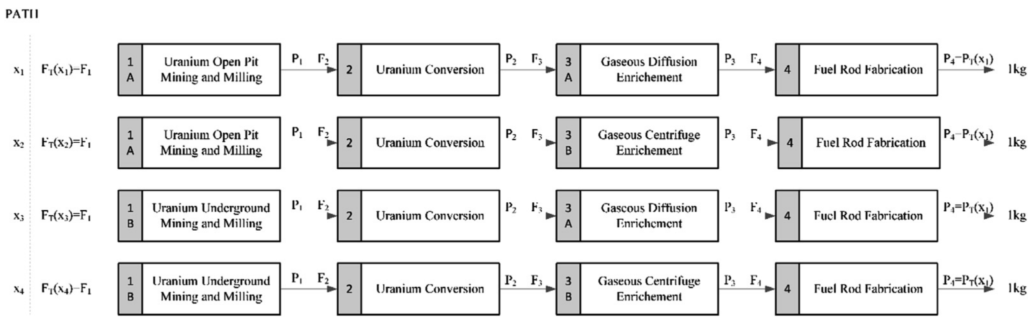

Fig. 4. Chains from uranium mine to the fuel fabrication.

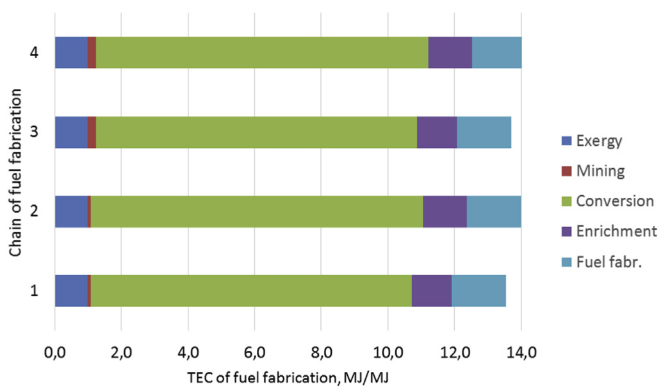

Fig. 5. Decomposition of TEC of nuclear fabrication.

$$e_j^* = \sum_i \left(a_{ij} - f_{ij}\right) e_i^* + \sum_k (\mathrm{GWP})_k e_{kj} \tag{10}$$

where:

e_j^* cumulative emission of greenhouse gasses in the j-th production branch,
e_i^* coefficient of cumulative emission of greenhouse gasses burdening the i-th product,
$(GWP)_k$ coefficient of global warming potential of the k-th gas,
e_{kj} coefficient of direct emission of the k-th greenhouse gas in j-th production branch.

Basing on results of calculation of cumulative emissions by means of (10) the LCE (life cycle emissions) can be determined. In such case the total LCE burdening the fabrication of considered useful product can be determined by means of formula [15,21]:

$$(\mathrm{LCE}) = \tau_n \sum_j \dot{G}_j e_j^* + \frac{1}{\tau} \left[\sum_m G_m e_m^* (1 - u_m) + \sum_r G_r e_r^* \right] \tag{11}$$

Emissions of GHG in full cycle by means of (10) and (11) has been investigated by Stanek and Białecki in Ref. [21]. Table 6 presents the comparison of direct and LCA GHG emissions for coal and imported natural gas.

Comparing the presented results of direct and cumulative emissions the necessity of application of cumulative emissions calculus in the case of GHG is evident. The direct emission of CO_2 is 1.6 times higher for coal than for natural gas. The cumulative ratio, comparing gas and coal, could only be at the level of 1.05–1.08. In other words, the GHG emissions burdening hard coal is quite similar to that of natural gas transported from huge distances. The methodology of life cycle emissions (10) and (11) and results from Table 6 have been used for analysis of coal, natural gas and nuclear power plant analysed previously by means of TEC. The obtained results are summarised in Table 7.

Results of emissions calculation for power technologies (direct and cumulative effects) shown that direct CO_2 is about 2.5 times higher in the case of existing coal technologies than that of NGCC. It is the result of the difference in energy efficiency and emission calculated by means of simple stoichiometric calculations Eq. (9). When cumulative life cycle emissions are compared the gas technology is only 1.5 times better. It proved that evaluation of production chains from resources extraction to electricity generation has to be made by the method of cumulative GHG. Additionally, the presented results shown that however the system exergy efficiency and TEC is extremely disadvantageous in the case of nuclear technology the GHG emission burdening the whole cycle is negligible in comparison to power technologies fed with chemical primary energy. According to the Polish energy policy, till 2030 installation of three nuclear power units is planned. The total power 4.8 GW of these units is expected. The influence of these investments on the structure of electricity generation is presented in Fig. 7.

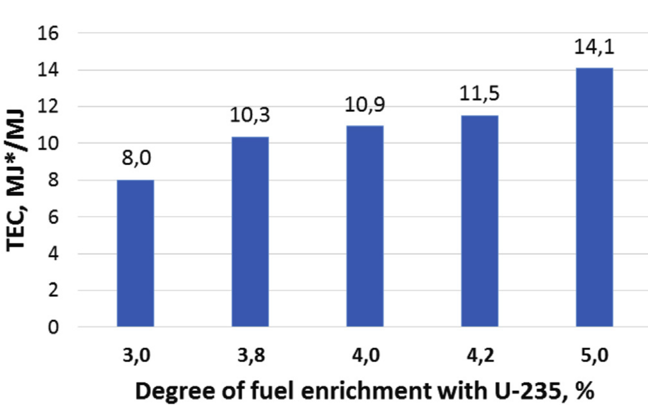

Fig. 6. Decomposition of TEC of nuclear fabrication.

Table 6
Comparison of direct and cumulative emissions from fuels [21].

No.	Fuel	Direct emission t CO_2/TJ	Cumulative emission t CO_{2e}/TJ
1.	Coal	92.0	95.8
2.	Coal (with methane leakage)	92.0	101.6–104.8
3.	Natural gas (GWP = 30, 4.2% leak.)	56.0	96.9

Table 7
Comparison of direct and cumulative emissions for power technologies.

No.	Technology	Direct emission t CO_2/TJ_{el}	LCA emission t CO_{2e}/TJ_{el}
1.	Coal average	230.0	254.0
2.	Coal BAT	184.0	203.0
3.	NGCC	93.0	161.3
4.	Nuclear existing	N/A	12.0
5.	Nuclear Gen III +	N/A	7.0

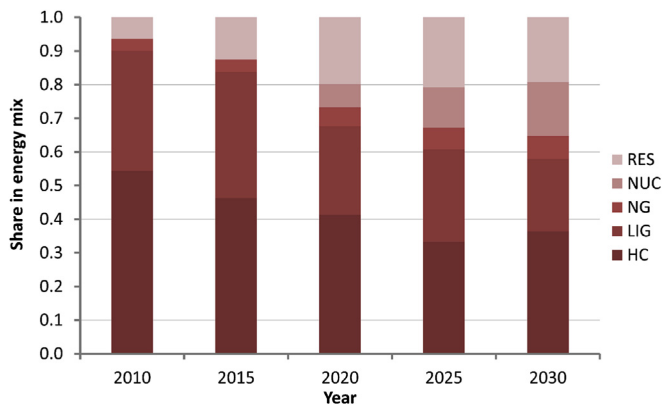

Fig. 7. Structure of Polish energy mix according to Polish energy policy (based on [10]). (HC – hard coal; LIG – lignite, NG – natural gas; NUC – nuclear energy, RES – renewable energy sources).

The results of GHG emission analysis have been introduced to the prognosis of Polish energy mix presented in Fig. 7. The results of cumulative GHG analysis in respect to the prognosis of Polish energy mix presented in Fig. 8.

The presented results shown evidently that even the system exergy efficiency and TEC is extremely disadvantageous in the case of nuclear technology for the planned share of nuclear energy in 2030 of about 15% the GHG burdening the energy mix will be significantly decreasing up to the level of 171 kg CO_{2e}/TJ_{el} in 2030. It means the decrease of more than 30% in relation to current (year 2010) energy mix based mainly on coal.

5. Economic evaluation

The economic evaluation mainly based on the data presented by NETL (National Energy Technology Laboratory) [13,17,18]. However,

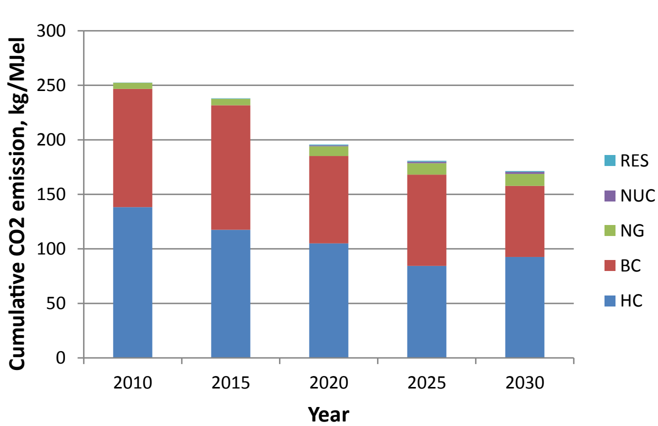

Fig. 8. GHG cumulative emissions for planned Polish energy mix.

it is necessary to show the similarities of the economic evaluation with the full life cycle TEC balance described by Eq. (8). In the mentioned equation the indices of specific thermo-ecological cost ρ_i should be replaced by the unit monetary costs and the indices of thermo-ecological cost ζ_k has to be replaced by the indices of external environmental cost that are presented in Table 8. The investment costs and maintenance costs are used in accordance with [13,17,18]. Table 9 presents the value of adopted economic values with the prediction of the range in which it can be changed. In this economic evaluation, the external environmental costs are taken into account. These costs are incurred indirectly through funds that must be spent on human health, renovation of buildings or additional fertilizer to compensate the losses in the surrounding environment. It should be noted that, these costs include the impact of meteorological conditions such as the dispersion of the pollutants [x]. The external environmental costs of air pollution emitted by the plant (External-1) and external costs of radiation (External-2) are the new components of the economic evaluation. The CO_2 cost is assumed at the level 15€/t of CO_2.

Table 9 presents the specific investment costs and operational costs, which are used according to [13,17,18]. The economic comparison for coal, gas and nuclear power plant are presented in Fig. 9.

It can be observed that the investment cost of nuclear power plant is significantly higher than those in the case of coal or gas power plant. However, the cost of both fuel and CO_2 emissions are higher in the coal and gas technology than in the case of nuclear plant. In the case of nuclear plant the CO_2-eq in full life cycle is estimated to be 0.5 EUR/MWh. The cost of fuel and CO_2 emissions are two main factor deciding of higher economic profitability of nuclear power plant. For this reason, the unit cost of electricity could be about 2 times lower in comparison to coal power plant.

6. Summary and final conclusions

In the article, the life cycle TEC (thermo-ecological cost), cumulative GHG emissions and economic methods are chosen to evaluate the entire nuclear fuel cycle. Based on these methods, the nuclear power plant has been compared with coal and gas units. The obtained results show that the direct exergy efficiency of the nuclear power plant is at the competitive level with the conventional coal power plant. However, in the case of the full cycle of uranium chain, the enormous exergy losses occur in comparison with the coal chain. The "uranium chain" is defined as uranium extraction processes up to delivery to the power station, whereas the "coal chain" is defined as processes of coal mining up to delivery to coal power plant.

It should be emphasised that in the formation of the exergy cost, the transformations of nuclear carriers and its nuclear exergy play the dominant role. The share of nuclear exergy in each TEC of mining, conversion and enrichment processes of the nuclear fuel is over 98%. The local exergy efficiency of fuel conversion and fabrication equals to 28.35% and 38.12%, respectively. The local exergy efficiency of centrifuge enrichment and diffusion enrichment amounts to 66.43% and 67.99%, respectively.

The exergy efficiency of whole nuclear power plant cycle is very low, which is caused by the extremely high exergy losses in major

Table 8
Externalities of emissions.

Emission	External cost w_k, €/kg
SO_x	12.81
NO_x	9.41
PM	7.00

Table 9
Economic costs [13,17,18].

	Nuclear plant	Gas plant	Coal plant	Estimated changes
Capital (EUR/kW)	3785	637	1739	± 30%
Fixed O&M (EUR/kW/year)	61	20	100	± 30%

stages of a nuclear chain. The "nuclear chain" is defined as mining, fuel fabrication, transport of fuel and electricity generation by the reactor. In the case of the existing technology, the exergy efficiency equals to 1.7%, whereas, in the considered generation III + is higher and amounts to 2.9%. Cumulative exergy losses could be defined as an inverse of the thermo-ecological cost.

The TEC analysis shows undoubtedly that the evaluation of nuclear power plant in terms of direct indices (direct energy efficiency or direct exergy efficiency) is insufficient; moreover, in some cases it can even be misleading. It is pointed out that the significant losses could appear in the early stages of the production chain. For this reason, it is necessary to evaluate power technologies using the cumulative exergy analysis taking into account the sustainability of non-renewable resources. The thermo-ecological cost methodology with the inclusion of the whole life cycle comprises this criterion. Nonetheless, the comprehensive analysis should take into account also the additional criteria such as economic and cumulative greenhouse gas emission.

In recent years, new uranium resources have been discovered, and a significant increase in knowledge in the field of extracting uranium occurred. Many factors indicate that uranium resources are so abundant that they will suffice for hundreds of years. The significantly long lifetime of uranium resources (rate of proven resources per current production) in comparison with the conventional fuels sources causes that the exergy of uranium resources can be omitted. Under such assumption and taking into account the high accessibility of nuclear resources, the TEC of nuclear electricity would be about 80 times lower than those in the case when uranium is treated as non-renewable resource of limited life-time.

The exergy unit cost of electricity generated by the nuclear power plant is significantly lower than those produced by conventional technologies. TEC of electricity generated by the nuclear power plant is very high, which is caused by the exergy losses. The results of cumulative exergy efficiency and TEC of nuclear technology are unfavourable when the assumption of high accessibility is omitted. However, in both cases, the cumulative GHG emissions are more acceptable than those emitted by the non-renewable power plant.

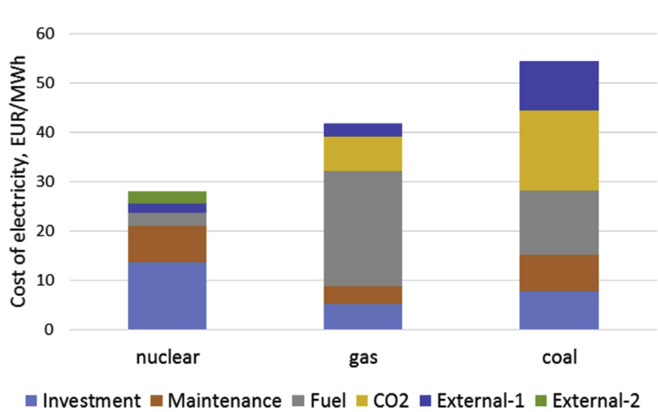

Fig. 9. Economic comparison of considered power plants.

The analysis presented in the paper shown that the direct CO_2 is about 2.5 times higher in the case of existing coal technologies than that of NGCC. It is the result of the difference in energy efficiency and emission calculated by means of simple stoichiometric calculations Eq. (3). When cumulative life cycle emissions are compared the gas technology is only 1.5 times better. It proved that evaluation of production chains has to be made by the method of cumulative GHG. Additionally, the presented results showed that however the system exergy efficiency and TEC are extremely disadvantageous in the case of nuclear technology the GHG emission burdening the whole cycle is negligible in comparison to power technologies fed with chemical primary energy.

Assuming the economic criterion, it is noticeable that the investment cost of the nuclear power plant is significantly higher than those of coal or gas power plant. Nevertheless, the cost of fuel and the fee of CO_2 are higher for coal and gas technology than for nuclear power plant. For this reason, the economic profitability of the nuclear power plant is essential. That also implies that the unit cost of electricity generated by the nuclear plant could be about twice lower than from other technologies. To sum up, taking into account presented criteria, it can be concluded that nuclear power plants are the competitive technologies in relation to the coal or gas power plant.

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Nomenclature

a_{ij}	coefficient of the consumption of the i-th product per unit of the *j*-th major product,
B_i^*	cumulative exergy consumption burdening the fabrication of *i*-th product exergy,
B_i, P_i	exergy of *i*-th useful product,
b	specific exergy,
b_s	specific exergy of the primary natural resource,
b_{sj}^{ch}	chemical exergy of the s-th non-renewable natural resource immediately consumed in the process under consideration per unit of the j-th product,
b_{sj}^{nu}	nuclear exergy of the s-th non-renewable natural resource immediately consumed in the process under consideration per unit of the j-th product,
c	mass fraction of carbon element C in fuel in kg C/kg fuel,
e_j^*	cumulative emission of greenhouse gasses in the j-th production branch,
e_i^*	coefficient of cumulative emission of greenhouse gasses burdening the i-th product,
e_{kj}	coefficient of direct emission of the k-th greenhouse gas in j-th production branch.
F_i	exergy of resources feeding the *i*-th production component (exergy of *i*-th component fuel),
f_{ij}	coefficient of the by production of the i-th product per unit of the j-th major product,
$\dot{G}_i$	nominal flow rate of the i-th raw material, semi-finished product or energy carrier supplied to the production process,

$\dot{G}_u$ nominal production rate of the useful u-th by product,
G_m consumption of the m-th energy carrier used for the construction of the installation,
G_{Pj} total yearly production of j-th main product,
G_r expected consumption of the r-th material or energy carrier used in repairs,
$(GWP)_k$ coefficient of global warming potential of the k-th gas,
I_i irreversibility (exergy losses) of i-th component of production chain,
LHV lower heating value of the fuel in MJ/kg or MJ/kmol,
M_{CO2} molar mass of CO_2, kg/kmol.
$(\mathrm{Mb})_{ch,i}$ molar chemical exergy of i-th component of solution, e.g. MJ/kmol,
(MR) universal gas constant,
p_{kj} total amount of the k-th waste product generated in j-th production branch,
$\dot{P}_k$ nominal flow rate of the k-th deleterious waste product rejected to the environment,
R total exergy of resources feeding the whole production chain,
s_{iu} replacement ratio in units of the i-th replaced product per unit of the u-th by-product,
T_0 absolute ambient temperature,
u_m expected recovery factor of the m-th material,
W_F burn-up ratio coefficient, GWd/t,
z_i molar fraction of i-th component in solution,

Greek symbols
ζ_k total thermo-ecological compensation cost of loses in the environment caused by the rejection of k-th contaminant,
$\eta_{B,\mathrm{el}}$ exergy efficiency of power plant,
$\eta_{E,\mathrm{el}}$ energy efficiency of power plant,
η_{th} thermal efficiency of the turbine cycle,
ρ_i,ρ_j TEC (thermo-ecological cost) of the i-th and j-th main product,
ρ_m,ρ_r thermo-ecological cost of the m-th material or energy carrier used in construction phase and thermo-ecological cost of the r-th useful good used in installations repairs,
ς_k index of the specific thermo-ecological cost of k-th deleterious waste product rejected to the environment,
τ_n annual operation time with a nominal capacity,
τ nominal lifetime of the installation.

Subscripts
ch chemical,
nu nuclear,
T total system boundary,

References

[1] Stanek W, Szargut J, Kolenda Z, Czarnowska L, Bury T. Thermo-ecological evaluation of nuclear power plant within the whole life cycle. In: Prof. Conf. ECOS'2014. Turku, Finland; 2014.
[2] Tani F, Haldi P-A, Favrat D. Exergy-based comparison of the nuclear fuel cycles of light water and generation IV. In: Reactors. Proc. Conf. ECOS 2010. Lausanne, Switzerland; 2010.
[3] Hermann W. Quantifying global exergy resources. Energy 2006;31(12): 1685–702.
[4] Statistical review of world energy. 2013. www.bp.com (last accessed 14.01.23.).
[5] Durmayaz A, Yavuz H. Exergy analysis of pressurized-water reactor nuclear-power plant. Appl Energy 2001;69:39–57.
[6] Lior N. Energy, exergy and thermoeconomic analysis of the effects of fossil-fuel superheating in nuclear power plants. Energy Convers Manag 1997;38:1585–93.
[7] Dunbar W, Scott M, Lior N. Exergy analysis of an operating boiling-water-reactor nuclear power station. Energy Convers Manag 1995;36(3):149–59.
[8] Rodriguez I, Alvarez-Velarde F, Martin-Fuertes F. Analysis of advanced European nuclear fuel cycle scenarios including transmutation and economic estimates. Ann Nucl Energy 2014;70:240–7.
[9] Gallo-Rivera Mancha-Navarro. Garrido-Yserte: application of the counterfactual method to assess of the local economic impact of a nuclear power station. Energy Policy 2013;62:1481–92.
[10] Energy Policy of Poland for 2030. Ministry of Economy 2009. www.mg.gov.pl, (last accessed September 2014).
[11] Energy and fuel management in 2011. Main statistical office. 2012. www.stat.gov.pl (last accessed September 2014) (in Polish).
[12] Celinski Z, Strupczewski A. Nuclear power. Warszawa: WNT; 1984 [in Polish)].
[13] Role of Alternative Energy Sources. Nuclear technology assessment. DOE/NETL-2011/1502. National Energy Technology Laboratory; August 8, 2012. www.netl.doe.gov (last accessed 14.01.23.).
[14] Szargut J, Ziębik A, Stanek W. Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. Energy Convers Manag 2002;42: 1149–63.
[15] Szargut J, Stanek W. Thermo-climatic cost of the domestic consumption products. Energy Feb. 2010;35(2):1196–9.
[16] Finneveden G, Ostlund P. Exergies of natural resources in life-cycle assessment and other applications. Energy 1997;22(9).
[17] Life Cycle Analysis. Existing pulverized coal (EXPC) power plant. DOE/NETL-403–110809. National Energy Technology Laboratory; September 30, 2010. www.netl.doe.gov (last accessed September 2014).
[18] Life Cycle Analysis. Natural gas combined cycle (NGCC) power plant. DOE/NETL-403–110509. National Energy Technology Laboratory; September 30, 2010. www.netl.doe.gov (last accessed September 2014).
[19] Stanek W. Method of evaluation of ecological effects in thermal processes with the application of exergy analysis. Silesian University of Technology Press; 2009 [in Polish)].
[20] Stanek W., Szargut J., Kolenda Z., Czarnowska L., Bury T.: Thermo-ecological evaluation of nuclear power plant within the whole life cycle. 27th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems ECOS 2014, Turku, Finland, 15–19 June 2014.
[21] Stanek W, Bialecki R. Can natural gas warm the climate more than coal? Fuel 2014;136:341–8.
[22] Szargut J, Stanek W. Thermo-ecological optimization of a solar collector. Energy 2007;32:584–90.
[23] Stanek W. Examples of application of exegy analysis for the evaluation of ecological effects in thermal processes. Int J Thermodyn March 2012;15(1).
[24] Szargut J. Exergy analysis: technical and ecological applications. Southampton: WIT-press; 2005. 2005.
[25] Kubowski P. Modern nuclear power plants. Warszawa: WNT; 2012 [in Polish].