Exergo-Ecological and Economic Evaluation of a Nuclear Power Plant within the Whole Life Cycle

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Abstract:

Polish energy sector is mainly based on coal combustion, which is responsible for the growth of CO_2 emission. At the same time, European trends toward sustainability and global warming mitigation may lead to significant changes in the Polish structure of electricity generation. According to the domestic energy policy, the increase in the number of renewable resources units and the first nuclear power units (3x1.6 GW_{el}) are planned in the perspective of the year 2030. The comparison of the nuclear power plant with the existing coal ones requires the evaluation of the whole life cycle along with the application of the common measure of the natural resources consumption. These requirements are fulfilled in the case of Thermo-Ecological Cost (TEC) analysis and cumulative emissions. It should be noted that TEC expresses the cumulative exergy consumption of non-renewable resources burdening the final goods such as electricity. TEC also takes into account the additional non-renewable exergy consumption required for mitigation of environmental losses caused by the rejection of harmful waste products. The results of TEC analysis of nuclear fuel cycle proved that the exergy efficiency of the entire life cycle of the resource utilisation is very low. The main cause of this imperfection appears in the stage of conversion, enrichment and nuclear fuel fabrication. Furthermore, the influence of power technology on greenhouse gas emissions (GHG) is elaborated. The GHG evaluation is most often based only on the analysis of direct emissions from the combustion. However, the direct analysis does not cover significant emissions of GHG, which appear in the process of mining and transportation of fuel. Therefore, in terms of GHG the comparison of power technologies has to be done using the cumulative calculus covering mining, processing, transportation, as well as end-use. It is carried out, that the coal and gas technologies have GHG emissions on a comparable level while nuclear power units are characterised with lower GHG emissions. In this paper, the mentioned technologies and their GHG emissions in the full cycle are presented. At the final stage, the economic criterion is also taken into account. In the paper, the results of a multi-criteria evaluation of different technologies are compared, including various cases of nuclear resources treating.

Keywords:

Exergy, Thermo-Ecological Cost, Life Cycle, Nuclear Power Plant, Greenhouse Gas Emissions.

1. Introduction

Continuous aspirations for further global economic growth accelerate the consumption of finished stock of non-renewable resources. Power sector plays a significant role in this consumption, as the electricity is one of the most important energy carriers for many manufacturing processes. At the same time, it is responsible for rejection of harmful wastes and greenhouse gasses (GHG) to the nature. It should be pointed out that in terms of the whole cycle of resources management the nuclear power chain is found low efficient in comparison with other power technologies fed with non-renewable primary energy [1,2]. However, the reported accessible stock of resources of nuclear energy is much more abundant as that of fossil fuels.

According to [2] and [3], the identified resources of uranium, which could be extracted at the economic profitability, are equal to 5.47 million tons. It represents a total exergy of about $0.44\cdot10^{12}$ 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. According to [3], it is predicted that besides the identified resources of uranium the unconventional and ocean resources of nuclear energy will be used. 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). The lifetime (R/P) is characterized by the resources (R) and production (P) [2, 3, 4]. According to [4], the lifetime (R/P) in the case of natural gas and oil is significantly limited and is equal to 56 and 53 years, respectively. 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 cycle was presented in details in [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 [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 emissions criterion are presented. The presented analysis is calculated in the full life cycle which finally gives the cumulative exergy efficiency.

It should be pointed out, that the nuclear chain is less responsible for the GHG emissions, as the electricity generation does not apply combustion process in that case. The nuclear technology is an interesting option for conventional power plants, because of two facts:

- relatively short lifetime of conventional primary energy resources, and long lifetime of nuclear resources,
- relatively large amount of GHG emissions burdening the fossil fuels combustion, and small in the nuclear chain.

In this paper, multi criteria comparison is presented. In the case of the analysis of the nuclear power sector on the depletion of non-renewable resources TEC theory has been applied. In this analysis, two cases have been considered: 1) nuclear primary resources are treated as non-renewable, 2) nuclear primary resources due to its huge availability are treated as renewable. In this paper, to analyse the total global warming impact, the analysis of cumulative equivalent emissions of CO_{2e} is proposed.

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. 1.

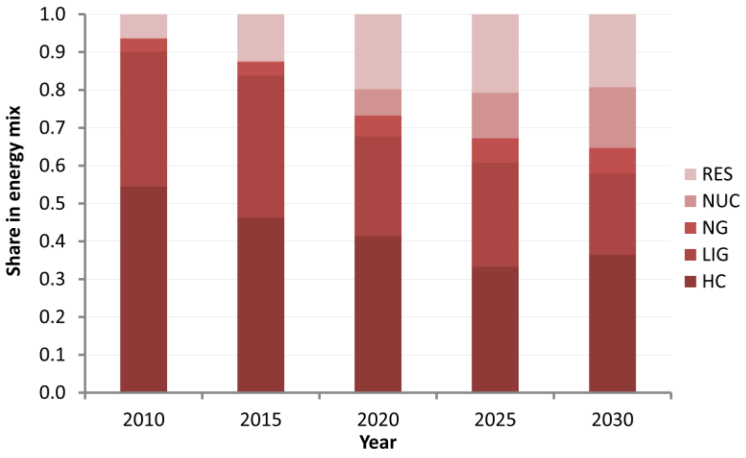

Fig. 1. Structure of Polish energy mix according to Polish energy policy (based on [10])
(HC – hard coal; LIG – lignite, NG – natural gas; NUC – nuclear energy, RES – renewable energy sources)

The comparison of nuclear power plants with coal and gas technology by means of economic criterion is additionally included.

2. Characteristic of the analysed systems

The basic factor deciding about the consumption of fuel and furthermore the emissions of waste products is energy or exergy efficiency. It has been assumed that the average net energy efficiency of coal power plant (PC) amounts to $\eta_{E,PC}$=40%. The assumed value is close to the average efficiency of electricity generation in the Polish energy system [11]. The best available PC's plant energy efficiency is approaching at present 50%. The net energy efficiency of best available technology (BAT) of combined gas and steam power plants (NGCC) fired with natural gas is approaching the level of $\eta_{E,CC}$=60%. For the assumed energy efficiencies the exergy efficiency is: $\eta_{B,PC}$=36.7% and $\eta_{B,CC}$ = 57.7%. The nuclear power plants are most often characterised by the energy efficiency of their thermodynamic cycle. This is far not enough to compare with other power plants because characterise only a part of the process of electricity generation. The balance boundary has to be assumed from the 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 energy efficiency (thermal efficiency) of the nuclear plant defined as $\eta_{th} = N_{el}/Q_{th}$ and *the burn-up ratio* W_F the energy and exergy efficiency of nuclear power plant can be calculated [1]. Table 1 shows the exergy efficiency for compared power technologies [1].

Table 1. Exergy efficiency of compared power technologies

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

)* average value for reactors existing in 2009: PWR (66%) and BWR (34%) [13]

It is evident that 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, in the case of nuclear power plant the energy or exergy efficiency is not a deciding factor on resource depletion or CO_2 emissions because of relatively high exergy losses in fuel fabrication chain [1] or because of combustion process absence. In this case 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 Thermo-Ecological Cost (TEC) [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. According to [17] and [18] the influence of the primary energy consumption on the results of total life-cycle analysis of PC and NGCC is about 97%. According to [19], the primary energy part of the coal power plant thermo-ecological cost cycle has been estimated at the level of 91%. It can be concluded that the emissions of GHG are mainly due to the operational phase of these power plants. 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 of nuclear power plant is presented in [20].

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

The evaluation of TEC and GHG emissions from assumed nuclear power technologies has been determined 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. 2.

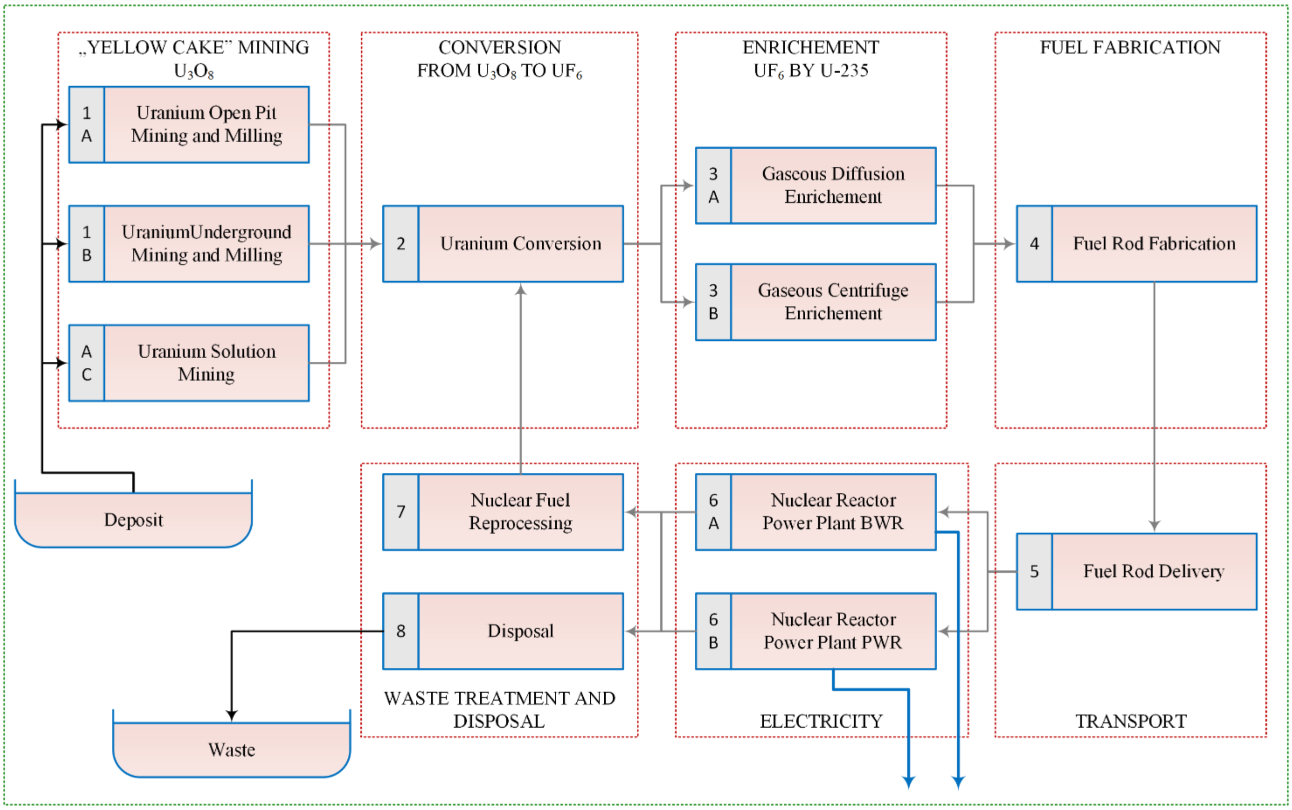

Fig. 2. The whole cycle of nuclear technology

3. Thermo-Ecological Cost (TEC) analysis

The physical cost of any product expressed by TEC 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]. This consumption appears in the production processes directly connected with the extraction of substances from the natural deposits, e.g. in the coal mine. Not all branches of economy are directly connected to the nature; however, due to interconnections in the production systems each product is linked to the natural resources. The TEC is also generated by the consumption of semi-finished products a_{ij} 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. In the balance presented in Fig. 1 the by-products are taken into account by the coefficient of by-production f_{ij}. TEC of the useful by-product should be determined by means of the avoided consumption of non-renewable exergy

[14]. The balance of TEC of *j*-th production branch includes also an additional consumption of resources connected with the rejection of wastes to the environment p_{kj}. This additional consumption is connected with the maintenance and operation of abatement installations as well as from the necessity of the compensation of other losses in the environment. The specific consumption a_{ij} of *i*-th useful product in *j*-th branch is dependent on the exergetic efficiency of the production process. For this reason, the exergy cost (TEC) is based purely on physical laws and its formation depends on the irreversibility of interconnected production processes. 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. 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.

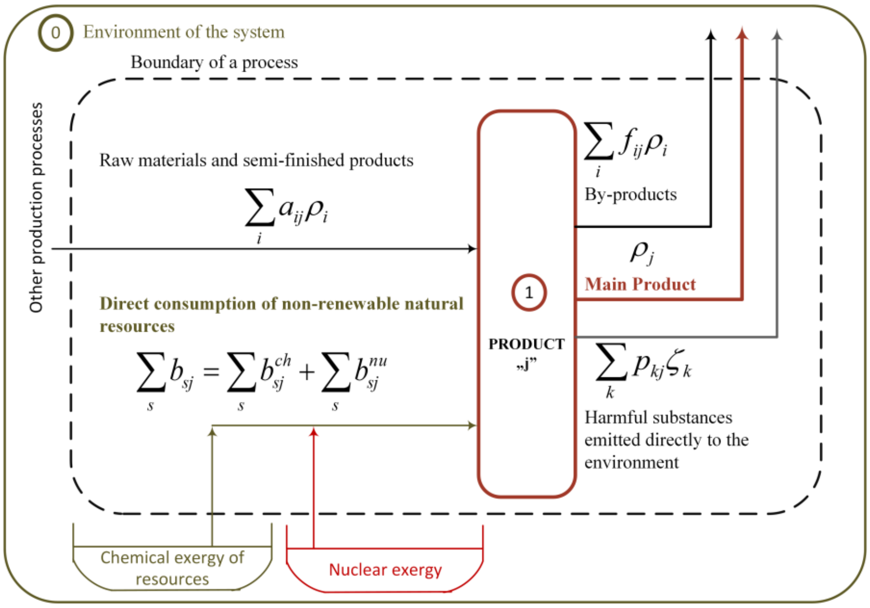

Fig. 3. Idea of TEC balance methodology

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:

$$\rho_j + \sum_i (f_{ij} - a_{ij})\rho_i = \sum_s b_{sj}^{ch} + \sum_s b_{sj}^{nu} + \sum_k p_{kj}\zeta_k \qquad (1)$$

The set of (1) should comprise all the branches of economy. However, it would be difficult to solve such problem. For this reason, in practical calculations only the strongly connected production processes are taken into account [14]. The TEC of given primary non-renewable resources in the nature is equal to its specific exergy $(TEC)_{prim} = b_s$ [1,19]. In the case of nuclear resources, the specific exergy b_s in the TEC balance (Fig. 1) should in general include not only the chemical exergy of natural resources b_{sj}^{ch} but also the nuclear exergy b_{sj}^{nu}. It should be checked, what is the influence of the chemical exergy and of the nuclear exergy of resources on the TEC calculation results using Eq.(1). The discussion of the importance of both parts of resource exergy on the TEC index is presented in [1].

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 Thermo Ecological

Life Cycle Assessment (TELCA) based on methodology, described in the previous section has to comprise the following phases:

1. Construction Phase encompasses the project, extraction of raw materials, fabrication of semi-finished products, transport expenditures in the construction phase. All these expenses influence the final thermo-ecological cost burdening the final useful product.
2. Operational phase is defined as a period of time between the end of the construction phase and a beginning of decommissioning phase. In processes utilising the non-renewable resources, this phase is predominant in the cumulative consumption of natural resources, mainly energy carriers.
3. Decommissioning phase of plant concerns the period at the end of the installation's life. In this phase, thermo-ecological cost results from expenditures to develop the remains of the system and, for example, some expenditures for reclamation of terrain.

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]. This function, expressing the yearly thermo-ecological cost has the following form:

$$(TEC)_{LCA} = \tau_n\left(\sum_i \dot{G}_i\rho_i + \sum_k \dot{P}_k\zeta_k - \sum_u \dot{G}_u\,\varrho_i s_{iu}\right) + \frac{1}{\tau}\left(\sum_m G_m\rho_m\,(1-u_m) + \sum_r G_r\rho_r\right) \tag{2}$$

where:

$\dot{G}_i$	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_r	expected consumption of the r-th material or energy carrier used in repairs,
$\dot{P}_k$	nominal flow rate of the k-th deleterious waste product rejected to the environment,
s_{iu}	replacement ratio in units of the i-th replaced product per unit of the u-th by-product,
u_m	expected recovery factor of the m-th material,
ζ_k	total thermo-ecological compensation cost of loses in the environment caused by the rejection of k-th contaminant,
ρ_i	thermo-ecological cost (TEC) of the i-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,
τ_n	annual operation time with a nominal capacity,
ϱ_i	specific thermo-ecological cost of the i-th major product,
τ	nominal lifetime of the installation.

The calculation of TEC has been done for all the nuclear chain presented in Fig. 2 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 chain have been determined independently on the TEC balance set formulated for the nuclear chain. In Table 3, the results of the TEC analysis of the nuclear chain from uranium mine (cradle) throughout fuel fabrication and transportation are summarised in Table 3.The TEC-1 has been calculated assuming that the uranium ore represents a non-renewable primary resource. The processed of 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 (on the power plant boundary): conversion – 28.35% and fuel fabrication – 38.12%. Also, the process of fuel enrichment is a resource consuming exergy as its local exergy efficiency amounts to: centrifuge enrichment – 66.43% and diffusion enrichment 67.99%. 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-1, 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. TEC-2 takes into account the high availability of uranium in compared with other non-renewable fuel sources. In this case, it can be seen the results lower than one that are also characteristic for renewables resources.

Table 3. Results of TEC analysis of fuel chain uranium mine – power plant

Stage	Product	Exergy of product b_P GJ/kg	Specific TEC-1 ρ_P MJ/MJ	Specific TEC-2 ρ_P MJ/MJ
Mining (open pit mine)	U_3O_8, yellowcake	464.03	1.006	0.01
Mining (underground)	U_3O_8, yellowcake	464.03	1.017	0.02
Conversion	UF_6 (0.7%)	370.01	3.568	0.04
Enrichment (centrifuge)	UF_6 (5.0%)	2642.91	5.370	0.07
Enrichment(diffusion)	UF_6 (5.0%)	2642.91	5.247	0.11
Fuel fabrication + transport	UO_2 (5.0%)	3445.41	14.089	0.18

Using the indices of TEC for the whole nuclear cycle, the TEC of electricity generated in nuclear power plant has been determined. Two cases of nuclear power plant and two cases of uranium ore have been examined. For the nuclear plant, the average existing nuclear power plant (69 PWR (66%) and 35 BWR (34%)) and average nuclear power plant of generation III+ have been developed. For the uranium ore, the difference in uranium availability was the main factor, which determines the results. The specific results of uranium ore are marked by superscript 1 and 2 to indicate the similarities with non-renewable and renewable natural resources, respectively. The results of the calculations are compared in Table 4.

Table 4. Results of TEC analysis of nuclear power plant

Power plant	Local exergy efficiency $\eta_{B,el}$, %	$(TEC)_{LCA}$ MJ*/MJ_{el}	System exergy efficiency $\eta^*_{B,el}$, %
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 **$0{,}73^2$**	1.73
Nuclear GEN III + (recycling)	46.2	33.78^1 **$0{,}42^2$**	2.96
Coal average in Poland	31.8	3.90	25.64

)* - cumulative

It can be observed, that in the case of the existing power plant 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 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 coal power plant that amounts to 25.6%. Processes of fuel conversion and enrichment have the dominant influence on the high exergetic cost of the whole nuclear chain. It can be additionally noticed that under the assumption of availability of nuclear resources the TEC for nuclear electricity is about 80 times lower than that obtained under the assumption that uranium ore is treated as a non-renewable resource.

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 readily evaluated using a simple relationship:

$$\varepsilon_F = n'_C \frac{M_{\mathrm{CO2}}}{(\mathrm{LHV})} \tag{3}$$

where: n'_C– fraction of carbon element in the fuel in kmol C / kg fuel or in kmol C / kmol fuel, LHV - lower heating value of the fuel in MJ/kg or MJ/kmol. In the case of fuel characterised by c – mass concentration of carbon element n'_C=c/12, M_{CO2} – molar mass of CO_2, kg/kmol.

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 greenhouse gasses (GHG) emissions takes the following form [15, 21]:

$$e_j^* = \sum_i \left(a_{ij} - f_{ij}\right) e_i^* + \sum_k (\mathrm{GWP})_k \, e_{kj} \tag{4}$$

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,

$e_{k\,j}$ coefficient of direct emission of the *k*-th greenhouse gas in *j*-th production branch.

Furthermore, based on results of calculation of cumulative emissions by means of (4) the life cycle emissions (LCE) 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]:

$$(\mathrm{LCE}) = \tau_n \sum_j \dot{G}_j \, e_j^* + \frac{1}{\tau}\left[\sum_m G_m e_m^* (1 - u_m) + \sum_r G_r e_r^*\right] \tag{5}$$

Emissions of GHG in full cycle by means of (4) and (5) has been investigated by Stanek and Białecki in [21]. Table 5 presents the comparison of direct and LCA GHG emissions for coal and imported natural gas.

Table 5. 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

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 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 (4) and (5) and results from table 3 have been used for comparative analysis of coal, natural gas and nuclear power plant analysed previously by means of TEC. The obtained results are summarised in Table 6.

Table 6. 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

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 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. Both – results of TEC and cumulative GHG analyses could have significant influence on sustainable exergetic factor and cumulative GHG emissions of the Polish energy mix.

5. Economic evaluation

The economic evaluation of the whole life cycle can be done by a similar formula as Eq.(2). In the mentioned equation the indices of specific thermo-ecological cost ρ_i should be replaced by the unit 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 7.

Table 7. Externalities of emissions

	Symbol	Unit	SO_x	NO_x	PM
External Cost	w_k	€ / kg	12.81	9.41	7.00

Assuming the specific investment costs and operational costs after [25] the average cost of electricity can be obtained. The comparison for coal, gas and nuclear power plant are presented in Fig. 4.

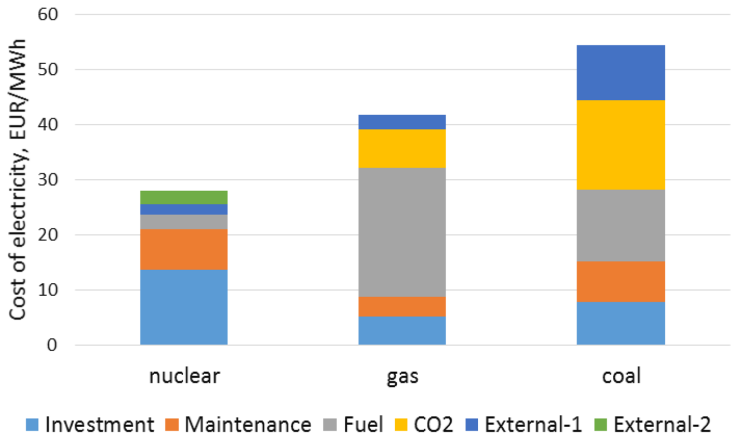

Fig. 4. Economic comparison of considered power plants

It can be observed that the investment cost of nuclear power plant is significantly higher than that in the case of coal or gas power plant. Nevertheless, the cost of both fuel and CO_2 emissions are higher in the coal and gas technology than in nuclear plant. The CO_2 cost is assumed at the level 15€/t of CO_2. These are two main factor deciding of higher economic profitability of nuclear power plant. In comparison to coal power plant, the unit cost of electricity could be about 2 times lower.

6. Summary and final conclusions

In the article, the life cycle thermo-ecological cost (TEC), 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 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 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. Two cases of TEC of uranium fuels are considered, due to the fact that the issue of depletion of uranium is smaller than the depletion of coal or gas resources. Taking into account the high accessibility of nuclear resources, the TEC of nuclear electricity is about 80 times lower than those in the case when this assumption is neglected.

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.

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 stations.

Nomenclature

a_{ij}	coefficient of the consumption of the i-th product per unit of the j-th major product,
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,
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,
$G_{P,j}$	total yearly production of j-th main product,
G_r	expected consumption of the r-th material or energy carrier used in repairs,
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,
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,
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,

$e_{k\,j}$ coefficient of direct emission of the *k*-th greenhouse gas in *j*-th production branch.

Greek symbols

ζ_k total thermo-ecological compensation cost of loses in the environment caused by the rejection of k-th contaminant,

η_{th} thermal efficiency of the turbine cycle,

ρ_i, ρ_j thermo-ecological cost (TEC) 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,

ϱ_i specific thermo-ecological cost of the i-th major product,

τ nominal lifetime of the installation.

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References

[1] Stanek W., Szargut J., Kolenda Z., Czarnowska L., Bury T.: Thermo-Ecological Evaluation of Nuclear Power Plant within the Whole Life Cycle. 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 Reactors. Proc. Conf. ECOS 2010. Lausanne, Switzerland 2010.

[3] Hermann, W., 2006, Quantifying global exergy resources, Energy, 31(12), pp. 1685- 1702.

[4] Statistical Review of World Energy 2013. www.bp.com, last accessed 23.01.2014.

[5] Durmayaz A., Yavuz H.: Exergy analysis of pressurized-water reactor nuclear-power plant. Applied Energy 69 (2001) 39-57

[6] Lior N.: Energy, exergy and thermoeconomic analysis of the effects of fossil-fuel superheating in nuclear power plants. Energy Conversion Management 38, (1997), 1585-1593

[7] Dunbar W., Scott M., Lior N.: Exergy analysis of an operating boiling-water-reactor nuclear power station. Energy Conversion Management 36-3, (1995), 149-159

[8] Rodriguez I., Alvarez-Velarde F., Martin-Fuertes F.: Analysis of advanced European nuclear fuel cycle scenarios including transmutation and economic estimates. Annals of Nuclear Energy 70 (2014) 240–247

[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 62 (2013) 1481–1492

[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, 2012. Main Statistical Office. www.stat.gov.pl, last accessed September 2014 (in Polish).

[12] Celinski Z., Strupczewski A.: Nuclear Power. WNT Warszawa 1984 (in Polish).

[13] Role of Alternative Energy Sources: Nuclear Technology Assessment. DOE/NETL-2011/1502. August 8, 2012. National Energy Technology Laboratory. www.netl.doe.gov, last accessed 23.01.2014.

[14] Szargut J., Ziębik A., Stanek W.: Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. Energy Conversion & Management. v. 42 (2002) 1149-1163.

[15] Szargut J., Stanek W.: Thermo-climatic cost of the domestic consumption products. Energy Vol. 35 Issue 2, Feb. 2010, pp. 1196-1199.

[16] Finneveden G., Ostlund P.: Exergies of natural resources in life-cycle assessment and other applications. Energy, Vol. 22, No. 9, 1997.

[17] Life Cycle Analysis: Existing Pulverized Coal (EXPC) Power Plant. DOE/NETL-403-110809. September 30, 2010. National Energy Technology Laboratory. www.netl.doe.gov, last accessed September 2014.

[18] Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant. DOE/NETL-403-110509. September 30, 2010. National Energy Technology Laboratory. 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 136 (2014), pp. 341-348.

[22] Szargut J., Stanek W.: Thermo-ecological optimization of a solar collector. Energy 32 (2007) 584–590.

[23] Stanek W., Examples of Application of Exegy Analysis for the Evaluation of Ecological Effects in Thermal Processes. International Journal of Thermodynamics, Volume 15, No. 1, March 2012.

[24] Szargut J.: Exergy Analysis: Technical and Ecological Applications. WIT-press, 2005 Southampton, 2005.

[25] Kubowski P.: Modern nuclear power plants. WNT 2012 Warszawa (in Polish).