ENERGY, EXERGY AND ENVIRONMENTAL QUALITY OF HARD COAL AND NATURAL GAS IN WHOLE LIFE CYCLE CONCERNING HOME HEATING

by

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The use of coal is suspected to have high environmental impact. Natural gas is treated as more environmentally friendly with high methane content and lower emission factors. In order to calculate the environmental impact in the whole life cycle associated with combustion of coal and natural gas all stages from "cradle to grave" should be taken into account. In particular, the transportation stage, especially in the case of life cycle analysis of gas, seems to be crucial. The distance of transmission of gas from gas fields, for instance located in Siberia, could be mainly associated with high diffuse emission of methane. The comparison of environmental impact assessment of coal and natural gas utilization for heating purposes is presented in the paper. The additional factor taken into account is localisation of boilers. In the analysis the coal is sombusted in combined heat and power plants equipped with flue gas treatment units is that released emissions are relatively remote from an urban area. In contrast, the natural gas is burned in small domestic installations with no additional FGT systems. The results of the analysis are given in 6 major impact categories. Moreover, the results of the life cycle analysis were brought into comprehensive thermo-ecological cost index, which is a cumulated exergy consumption of non-renewable resources. The results presented in the paper refer to the contemporary problem of the choice of energy sources in the context of its overall environmental efficiency.

Key words: *life cycle analysis, coal, natural gas, environmental impact, exergy, energy*

Introduction

In recent years, the downward trend in primary energy production is observed. This trend may, at least in part, be attributed to supplies of raw materials, which are becoming exhausted and/or their extraction from the limited resources is considered as uneconomical. On the other hand, the downward trend could be caused by EU policy focused on renewable energy implementation.

In 2012, the production of primary energy in the EU-28 equaled 794.3 million tonnes of oil equivalent (toe). More than one fifth of the EU-28's total production of primary energy consisted of renewable energy sources (22.3%). Additionally, solid fuels (20.9%, largely coal), natural gas (16.8%) and crude oil (8.9%) were produced [1]. Poland has 1.4% of the world's coal production (share of total 2014), whereas Germany and the Czech Republic

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1.1 and 0.4% [2], respectively. It should be noted that Europe imports large amounts of natural gas.

According to [3], emissions to the atmosphere, due to the electricity production, are higher for coal than for natural gas. In tab. 1, values for the 4 basic pollutants emitted into the atmosphere by coal, oil and natural gas are shown. The values for coal and oil are similar. However, comparing them with natural gas (from Russia) it could be noticed that values for CO_2, SO_2 and NO_x are more than 2.5, 63 and 3 times higher, respectively. Only the values of methane emission are similar for all presented fuels.

Table 1. The values of direct emissions to the atmosphere of selected pollutants during the electricity production [3]

Compound	Unit	Hard coal	Oil	Natural gas (from Russia)
NO_x	g/kWh	1.44	1.27	0.39
SO_2	g/kWh	2.52	2.31	0.04
CO_2	g/kWh	989	886	383
CH_4	g/kWh	1.67	1.08	1.39

Natural gas is a non-renewable fossil fuel, which is one of the commonly used sources of energy. Its composition varies depending on the place of production. However, more than 90% of the composition is methane. In Russia, natural gas is extracted in Siberia and the area is considered to be the biggest source of this fuel.

Natural gas extracted in Russia boasts the high content of methane reaching 96.2%. The average concentrations of other hydrocarbons are as follows: C_2H_6 – 1.2, C_3H_8 – 0.3, C_4H_{10} – 0.1, C_5H_{12}+ – 0.1. Concentration of N_2 and CO_2 are 1.8 and 0.3, respectively [4].

The emission of GHG from combustion of natural gas is relatively lower than GHG from other fossil fuels. For hard coal, this emission is estimated on the level of 1,000 g CO_2/kWh and for natural gas about 390 g CO_2/kWh. Similarly, emission of SO_2 for natural gas is about 0.1 g/kWh and for hard coal as high as 2.5 g/kWh. The average emission of NO_x is also lower for natural gas (0.39 g/kWh) comparing to hard coal (1.41 g/kWh) [3].

The combustion of natural gas seems to be relatively less harmful to the environment than the combustion of hard coal. The values presented above include only combustion omitting other stages of life cycle. However, the transport of natural gas requires large number of raw materials for investments, including pipelines. The energy demand required in compressor stations that pump the gas from remote locations to the target are significant. Each element, which is used for the flow of the gas has its separate impact on the environment and should not be omitted in the overall environmental impact analysis.

The aim of the study is to compare the environmental impact of home heating based on two different types of combustion such as coal and natural gas combustion. The Russian gas was taken as an example due to the high volume representing 44% of all fuel that is imported by EU from this direction [5]. The analysis is done based on the example of a model settlement, which assumes the population of 2,000 people living in detached houses. The area of the settlement is equal to 0.25 km^2, and it is assumed to be placed in Northern Germany. The settlement is receiving natural gas from the Nord Stream pipeline end section in the German town of Lubmin.

In this paper, two scenarios of heating system for the settlement are considered. In the first scenario, home heating systems are equipped with bi-functional gas boilers with a capacity of 20 kW in a distributed system – each has its separate heating value. For the presented analysis, the net calorific value of 34 MJ gas/m^3 is used, and the average gas composition for natural gas extracted in Russia is quoted above. The second scenario involves heating and water heating by hard coal heating plant with a capacity of 10 MW.

In the analysis, the environmental effects of gas boilers construction and heating plant are omitted. On the basis of life cycle analysis (LCA) approach, the environmental impact of two scenarios is expressed in major impact categories. The categories that are considered are as follows:
– abiotic depletion (AD),
– climate change – 100 years horizon (CC100),
– climate change – 500 years horizon (CC500),
– human toxicity (HT),
– photo-oxidant formation (POF),
– acidification (AC),
– ozone layer depletion (OLD), and
– eutrophication (EU).

The allocation procedure is made for coal and gas combustion on which the final impact on human toxicity is calculated.

Taking into the consideration the whole life cycle of heat production from coal and environmental impact of each stage – the overwhelming majority is connected with coal combustion. In the manuscript the average coal is used. The environmental impact of pipelines in case of coal is insignificant – due to short distance and lack of energy consuming devices (unlike in case of natural gas). The average distance of effective environmental impact in categories, like human toxicity, from heating plant of the size mentioned in the manuscript, is limited to a dozen of kilometres. This makes it possible to place the plant in the area that on one hand is distant enough to make the impact very small and on the other hand makes it technically possible to deliver heat to houses.

The analysis is divided into two phases. The first phase (phase I) includes the construction and operation of the pipeline, the usage of main materials and energy carriers, as well as gas losses during transport. The second phase (phase II) takes into account the same combustion of gas in order to produce heat for domestic heating and hot water in bi-functional gas furnaces. The analysis was made using CML2001 methodology in accordance with ISO 14040 series standard.

Comparison of LCA of coal and LCA of gas

For the LCA data for a newly built Nord Stream gas pipeline is used [6]. The main materials used to build the pipeline, energy consumption for operation, as well as the methane emissions (leakage), are taken into consideration. The most important data used in this analysis are given in tab. 2. The annual flow of natural gas is expected to reach 27.5 billion m^3, in one of the two parallel pipelines. The lifetime of the pipeline is designed for 50 year. The total volume of gas in this time would be 1.375E−12 m^3.

The approximate distance for the gas to be covered from the source to the final consumer is 3,834 km. There are three main sections: sea section of Nord Stream – 1,224 km, overland section in Russia (Wyborrg – Raizowiec) – 750 km and overland section connecting Nord Stream with gas source – 1,860 km [6, 7]. The gas losses during transportation are assumed on the level of 2%.

The climate change impact category is contributed by 0.502 kg CO_2 eq. for each m^3 of transported gas. Unitary results for different elements of the system are shown in tab. 3.

The gas losses in equivalent CO_2 emissions during transportation (73.75%) as well as electricity consumed for pumping the gas (26.21%) have the highest impact on the selected factors. The impact of pipeline elements is low (0.04%) and is the result of long pipeline lifetime. Gas and electricity losses are not amortized, since their effect is continuous, and hence their contribution is large in the obtained results.

Table 2. Materials and energy used for construction and operation of Nord Stream gas pipeline during the whole life time (50 years) [6, 7]

Element of the system/type of material/ substance/energy	Quantity	Unit	Quantity related to 1 m^3 of gas (during the whole life period)
Pipeline			
Steel	1,070,207.5	t	7.78333E−07
Internal epoxy coating	1,223.5	t	8.89818E−10
The outer shell 3LPE	25,411.0	t	1.84807E−08
Concrete weight coating	1,225,503.0	t	8.91275E−07
Aluminum anodes	3,111.0	t	2.26255E−09
Zinc anodes	2,822.0	t	2.05236E−09
Joint coating:			
W1: Shrink sleeve	501.5	t	3.64727E−10
W2: Polyurethane	4,326.5	t	3.14655E−09
Rock material – gravel	830,556.5	m^3	6.04041E−07
Pumping stations			
Quantity (per year)			
The amount of energy in the pumping station at Portovaya	3,206,160,000	kWh	0.1166
The amount of energy in the section to the Portovaya (20 stations)	1,752,000,000	kWh	0.0637
Natural gas emitted from losses to the atmosphere (2%)	550,000,000	m^3	0.0200
Natural gas emitted from losses to the atmosphere (2%)	406,968,320	kg	0.0148

Table 3. The impact of individual elements of the construction and operation of the pipeline on global warming in 100 years horizon (IPCC GWP 100a)

Element of the system	Value [kg CO_2 eq/m^3]
Gas losses	0.37
Steel	1.59E−06
Concrete	0.000233
Aluminium anodes	2.26E−09
Gravel	1.70E−06
Polyurethane foam	1.36E−08
Energy consumption	0.131
Total	0.502

As in the case of the category climate change, in the case of other categories can be seen the predominant influence of energy consumption and gas losses on the overall share of the environmental impact. However, the gas losses are visible only in two impact categories such as the climate change (500 years horizon) impact category and photo-oxidants creation with share on the level of 45% and 90%, respectively. Natural gas consists mainly of methane (about 96%) which is a greenhouse gas; hence the results are fairly predictable. In other impact categories, the use of energy is of great importance. Only in the category of climate change (500 years horizon) and human toxicity, a small influence of concrete used in construction can be observed, with the share well below 1%.

In terms of the human toxicity impact, the electricity consumption (99.3%) has the main participation. In addition, concrete and steel used in the construction of the pipeline have the negligible impact, their share is equal 0.54% and 0.15%, respectively.

Summary measures for the whole phase I and II of all categories of impact are presented in tab. 4.

Table 4. Environmental impact of all elements present in phase I and II given for natural gas in major impact categories

IC	Unit	Phase I		Phase II		
		Impact related to 1 m^3 of gas	Impact related to GJ	Impact related to 1 m^3 of gas	Impact related to GJ	Share of phase II
AD	kg Sb eq	1.13E−03	3.33E−02	2.13E−02	6.25E−01	94.94%
AC	kg SO_2 eq	2.06E−04	6.05E−03	2.31E−03	6.79E−02	91.82%
EU	kg PO_4 eq	4.08E−05	1.20E−03	4.73E−04	1.39E−02	92.05%
CC500	kg CO_2 eq	2.30E−01	6.76E+00	2.40E+00	7.05E+01	91.25%
CC100	kg CO_2 eq	5.02E−01	1.48E+01	2.59E+00	7.62E+01	83.77%
OLD	kg CFC-11 eq	1.40E−08	4.13E−07	3.38E−07	9.95E−06	96.01%
HT	kg 1.4-DB eq	5.71E−03	1.68E−01	4.35E−01	1.28E+01	98.70%
POF	kg C_2H_4 eq	9.73E−05	2.86E−03	2.78E−04	8.17E−03	74.07%

In all categories, the environmental impact is much higher in case of the phase II. The share ranges from 74% of the total (phase I and II) for photo-oxidants formation to 98.7% for human toxicity.

Analysis of the environmental impact of coal combustion has been made throughout the life cycle. It includes, within its scope, the combustion of coal in 10 MW boiler, mining, transportation, demand for water, ash and post-combustion residues removal and the energy consumption, mainly electricity. The average emissions for industrial heat in Germany (Stoker boiler) are used. The net calorific value of coal used in this of calculation is 28 MJ/kg.

The case of coal combustion, similarly to the case of natural gas analysis, is divided into two phases. The first phase covers all stages of the life cycle of the coal combustion (mining, transportation, storage, ash removal, and energy and water consumption). The second phase includes the incineration and energy recovery. The share of phase I and II are accepted on the level for Germany [8]. Summary measures for the first and second phase of all categories of impact are presented in tab. 5.

Table 5. Environmental impact of all elements present in phase I and II given for coal in major impact categories

IC	Unit	Phase I		Phase II		
		Impact related to 1 m^3 of gas	Impact related to GJ	Impact related to 1 m^3 of gas	Impact related to GJ	Share of phase II
AD	kg Sb eq	9.50E−03	3.45E−01	9.50E−03	3.45E−01	50%
AC	kg SO_2 eq	9.20E−03	3.22E−01	1.38E−02	4.84E−01	60%
EU	kg PO_4 eq	2.20E−03	7.87E−02	1.80E−03	6.44E−02	45%
CC50	kg CO_2 eq	2.80E−01	9.98E+00	2.52E+00	8.99E+01	90%
CC10	kg CO_2 eq	2.93E−01	1.04E+01	2.64E+00	9.40E+01	90%
OLD	kg CFC-11 eq	5.00E−08	2.00E−07	5.00E−08	2.00E−07	50%
HT	kg 1.4-DB eq	3.28E−01	1.17E+01	7.66E−01	2.73E+01	70%
POF	kg C_2H_4 eq	4.50E−04	1.58E−02	5.50E−04	1.93E−02	55%

The results of the impact analysis of coal and gas show a significant influence of the analysed systems on the environment. Any use of fossil fuels and non-renewable resources is associated with high emissions of many substances harmful to the environment. The summarized comparison of both cases is given in fig. 1.

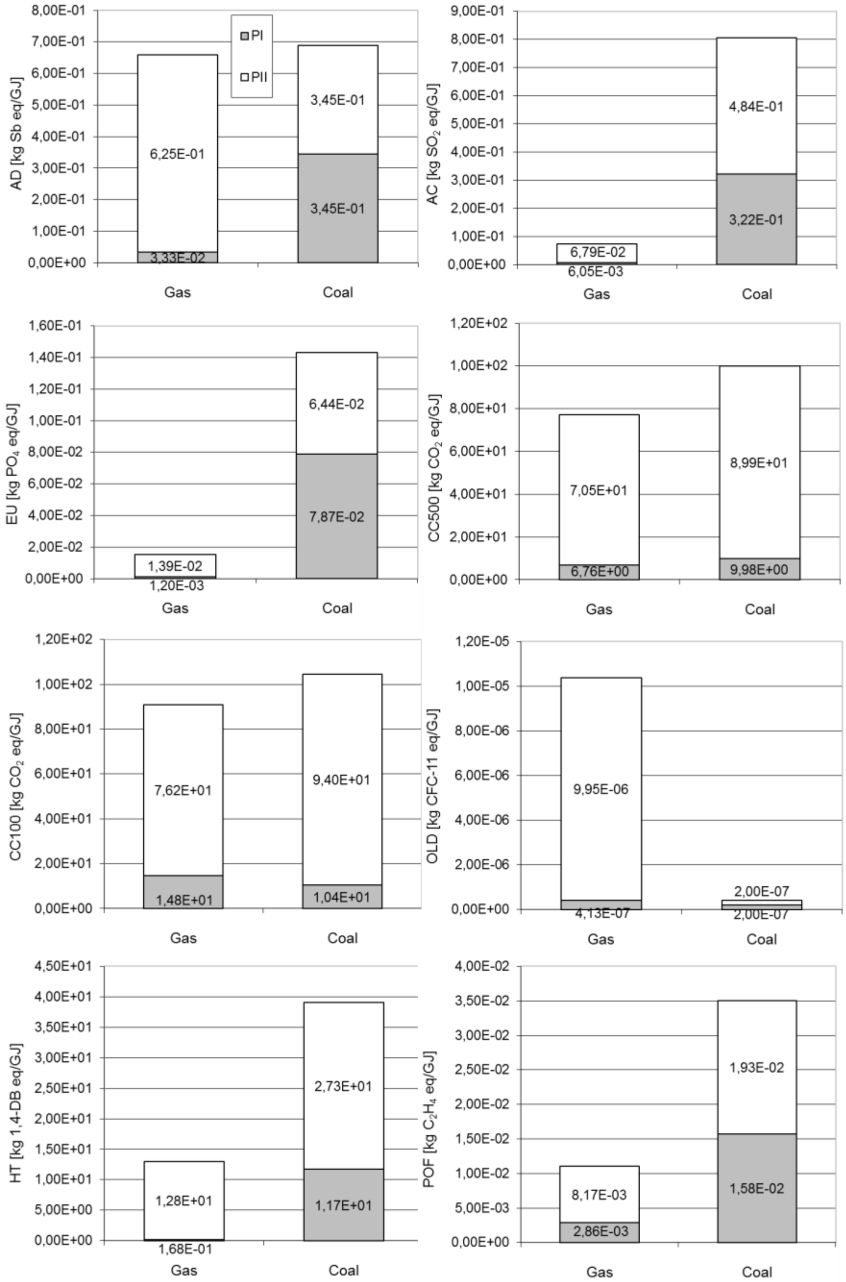

Figure 1. Comparison of environmental impact of natural gas and hard coal in different impact categories

Comparing the results in tab. 4 and tab. 5 for the entire analysis of coal and natural gas, coal mining has greater influence on the environment. Moreover, every category of equivalent emissions of coal is higher than category ozone layer depletion. Similarly, in the case of climate change impact category values are similar. In the category of human toxicity, the value of natural gas has three times lower emissions of equivalent value.

Comparing the values for the entire analysis of coal and natural gas, coal seems to have a higher environmental impact. In almost all categories the equivalent emissions is higher for coal with the exception of ozone layer depletion impact category. In case of climate change the impact is similar. In the human toxicity category natural gas has more than three times lower equivalent emissions value.

However, it should be noted that the classic LCA does not take into account the impact at a particular location, but only average values of emission. It seems not to be quite logical especially in human toxicity impact category, where population density in closest vicinity must have its importance. Therefore, in order to assess the real impact of using coal and gas for heating purposes the localization should be taken into account.

Localization

Similar emission in different area could have quite different environmental effect. If we compare two installations – one placed on the desert and the second placed in dense populated area the scale of environmental impact – especially for human beings – could be significantly different.

The general concept is that the environmental impact in particular impact category could be assessed on the basis of emission data, together with sensitivity of the area, that could be affected by this emission. The sensitivity mentioned above would be different for different impact category. If the impact category is human toxicity then population density could be treated as the measure of sensitivity.

The local conditions could be described by the localization coefficient (LoC) which should be calculated for all impact categories and all stages of life cycle.

Each stage of life cycle should have different allocation coefficient because its processes are carried out in different location with different senilities. It could be defined by the eq. (1) [9]:

$$\mathrm{LoC}_{\mathrm{H,LCz}} = \frac{\mathrm{PD}_{\mathrm{LCz}}}{\overline{\mathrm{PD}}} \tag{1}$$

where $\mathrm{LoC}_{\mathrm{H,LCz}}$ – allocation coefficient for human toxicity on the stage of life cycle LCz, $\mathrm{PD}_{\mathrm{LCz}}$ – population density in particular area (affected by the processes carried out during life cycle stage LCz), $\overline{\mathrm{PD}}$ – average population density in reference area.

In the process of evaluation local area properties are represented by localization matrix (LoM).

If value of LoC equals 1, this means that the influence of localization is not important. In other words the vulnerability of the effected is the same as average. This situation is assumed in classic LCA. The value of LoC is higher than 1 it means that the localization makes the real environmental impact stronger due to higher vulnerability of the terrain than reference area. If the value is below 1 the real environmental impact is weaker due to lower receptors concentration that the average I reference area.

LoM is the matrix $k \times z$ where k is the number of impact categories and z is the number of stages of life cycle. Values of allocation coefficients linked with global phenomena are constant and equal 1. It means that LoC_{CC} and LoC_{PO} are present in the matrix but their values are always 1.

Results of inventory and weighting are present in IM matrix which dimensions should be the same as dimensions of AM matrix. If we make Hadamard's product of matrix IM and LoM we get allocated impact matrix (^{Lo}IM), given by the eq. (2):

$$^{Lo}\mathrm{IM} = \mathrm{IM} \cdot \mathrm{LoM} \tag{2}$$

For the comparison of several cases, the reference area presented above could be defined as an area covering all places affected by evaluated system or systems. It means that it should also include all linked emission receptors. An immission approach would make it possible to carry out the environmental evaluation in particular location taking into account local area properties.

The emission approach assumes that the sensitivity of the whole area affected by one installation in one life cycle stage is the same. In some cases it could lead to major errors. The shape of the terrain, meteorological conditions, *etc.* are not used in the emission approach. Those factors could be important because it could make concentrations of various substances very high in some places – which could lead to strong environmental impact for specific elements of the environment. The emission approach in fact is based on average values of immission that sometimes would not form the perfect solution.

In order to include the local conditions, the recalculations of allocation coefficients present in LoM matrix should be made. The value of LoC depends on average long term immission and sensitiveness of different points inside impact area of the system.

The area under analysis should comprise all environmental impact receptors coming from the evaluated system.

The area is represented by the immission matrix of the test area IMM comprising immission values INV in grid points of test area. The dimensions of the matrix are *x*-max and *y*-max. Firstly, the grid on the test area should be placed and then the immission values in those points should be calculated. Finally, then the immission values should be introduced into the matrix IMM. The number and dimensions of inner cells inside the grid could be different in different systems. It depends on the level of accuracy that should be reached. The area under analysis could be larger than necessary minimum and it could be for instance the same as the reference area.

Relative immission matrix (RIMM) should be created on the basis of immission matrix (IMM) and it would comprise the relative immission vales (RIV) given by the following eq. (3) [10]:

$$\mathrm{RIMV}_{x,y} = \frac{\mathrm{IMV}_{x,y}}{\sum_{x=1}^{x-\max} \sum_{y=1}^{y-\max} \mathrm{IMV}_{x,y}} \tag{3}$$

The dimensions of matrixes RIMM I IMM should be identical.

Along with the creation of RIMM, the sensitivity of test area array SM, which would contain sensitivity values SV, should be created. The SM matrix is the basis for the creation of relative sensitivity matrix (RSV). The matrix should be connected to the grid covering the same area that covers IMM matrix. The dimensions and number of cells should be the same as well.

RSV present in RSM could be calculated using eq. (4):

$$\mathrm{RSV}_{x,y} = \frac{\mathrm{SV}_{x,y}}{\overline{\mathrm{TASV}}} \tag{4}$$

where $\overline{\mathrm{TASV}}$ – average test area sensitivity value, $\mathrm{SV}_{x,y}$ – sensitivity of cell x, y.

Finally, RIMM and RSM would be the starting point to determinate allocation coefficient AC according the following equation:

$$\mathrm{LoC} = \mathrm{RIMM} : \mathrm{RSM} \tag{5}$$

As it is seen, this is Frobenius product of matrixes RIMM and RSM. In other words, it is internal product of two components treated as a vectors or sum of elements of Hadamard product, according to the eq. (6):

$$\mathrm{LoC} = \sum_{x=1}^{x-\max} \sum_{y=1}^{y-\max} \mathrm{RIMV}_{x,y} \mathrm{RSV}_{x,y} = tr(\mathrm{RTAIMM}^{\mathrm{T}}\ \mathrm{RTASM}) = tr(\mathrm{RTAIMM}\ \mathrm{RTASM}^{\mathrm{T}}) \tag{6}$$

The LoC defined in that way comprises information about local properties of the environment, the concentration of pollutants and finally sensitivity of the area in the particular impact category. It could be treated as weighting value for potential negative impact on the environment under specific conditions and specific localization.

Localization of gas and coal boilers

In order to calculate allocation indicator, only the human toxicity, which is the impact categories, should be selected. When calculating the following assumptions are made:

- coal heating power is 10 MW,
- the power of a single gas boiler installed in each of the homes at an average of 20 kW,
- model settlement unit has 2,000 inhabitants,
- the average size of building plot size is 500 m^2,
- the size of model settlement units is 0.25 km^2,
- the average population density of model settlement unit is 8,000 pers./km^2,
- the range of power plant emission is 10 km^2,
- the population density of the reference area (assuming the area of Germany and the actual population density) 229 pers./km^2,
- the population density of the area where the range is the emission of gas furnaces in 2,000 pers./km^2, and
- the population density of the area where the range is the emission of heat 200 pers./km^2.

The location procedure presented in this paper applies only to the place where combustion of coal and gas takes place. In both cases, the results that are presented in the figures are calculated only for phase II. The localization procedure could not be executed in the case of phase I due to lack of specific date about localization details of retrieval and transportation process. Scheme of localization of the test area and reference area are presented in fig. 2.

The overall environmental impact for human toxicity impact category is defined by the eq. (7):

$$\mathrm{II}_{\mathrm{HT,TOTAL}}^{\mathrm{LoC}} = \mathrm{II}_{\mathrm{HT,PHI}} + \mathrm{II}_{\mathrm{HT,PHII}}^{\mathrm{LoC}} = \mathrm{II}_{\mathrm{HT,PHI}} + \mathrm{II}_{\mathrm{HT,PHII}} \cdot \mathrm{LoC}_{\mathrm{HT}} \tag{7}$$

where $\mathrm{II}_{\mathrm{HT,TOTAL}}^{\mathrm{LoC}}$ – total impact indicator in the human health impact category for the life cycle (phase I and phase II) taking into account the location of the system, $\mathrm{II}_{\mathrm{HT,PHI}}$ – impact indicator in the human health impact category for the phase I without taking into account the location of the system, $\mathrm{II}_{\mathrm{HT,PHII}}^{\mathrm{LoC}}$ – impact indicator in the human health impact category for the phase II taking into account the location of the system, $II_{HT,PHII}$ – impact indicator in the human health impact category for the phase II without taking into account the location of the system, LoC_{HT} – location indicator calculated for the human health impact category.

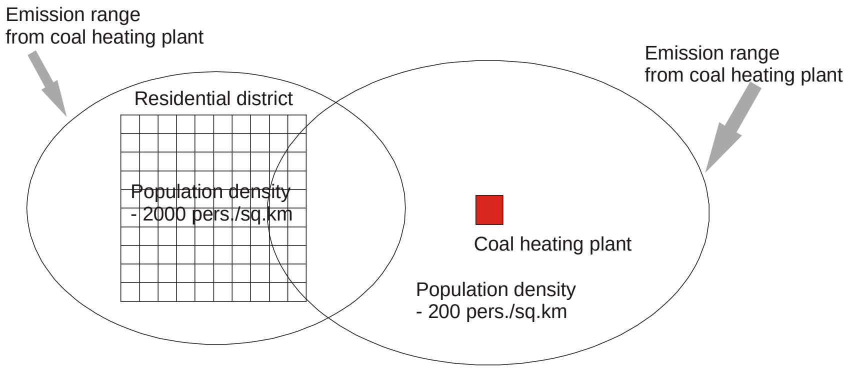

Figure 2. Scheme of localization of the test area and reference area

In adopted location the localization coefficient LoC for gas and coal was calculated and the value is:
- for natural gas – 8.73, and
- for hard coal – 0.87.

The II_{HT} for natural gas for phase I and II are respectively: 1.68E−01 and 1.28E+01 kg 1.4-DB eq/GJ. The value of hard coal for phase I and II are respectively: 1.17E+01 and 2.73E+01 kg 1.4-DB eq/GJ.

Final localized coefficients for both fuels including whole life cycle are:
- $II^{LoC}_{HT,TOTAL,coal}$ = 35.60 kg 1.4-DB eq, and
- $II^{LoC}_{HT,TOTAL,coal}$ = 111.84 kg 1.4-DB eq.

Calculated indicators for the location of coal and gas have shown that in the category of human toxicity, natural gas has finally almost three times higher environmental impact than coal. It is related to fact that the gas is combusted in furnaces, in households where emission takes place directly in the densely populated area. The coal is combusted in a central heating plant away from inhabited places. Although the emission range of the heating covers the entire unit settlements, the values of pollutant concentration are so small that, comparing to the gas heating, the effect of settlement unit on the environment is smaller.

Exergy evaluation

Thermo-ecological cost is defined as the cumulative exergy consumption of non-renewable natural resources associated with any product, taking into account the necessity to prevent and compensate losses caused by the release of harmful substances into the environment [11]. This technical cost, which is based on physical laws, is expressed in MJ of non-renewable exergy per physical unit of considered product, *e. g.* kg of product, kmol of product or MJ exergy of product. Many things that are used on a daily basis are based on many production processes with different use of materials and goods which are connected to each other. To sum up, the set of TEC equations applies to interconnected production chains of any product. However, it should be noted that the cost of product at ground, in other words the cost of natural resources, is equal to its exergy b_{sj}.

The idea of TEC for both analysed phases in the entire life cycle is presented in fig. 3. It should be noted that the analysed scenarios are connected with many others processes and products, this is indicated by the dot-lines, in order to make it more legible to the reader. The TEC of gas distribution, which is expressed in MJ of exergy per year, is presented in tab. 6. The phase I and II for the coal combustion were presented in details in [12].

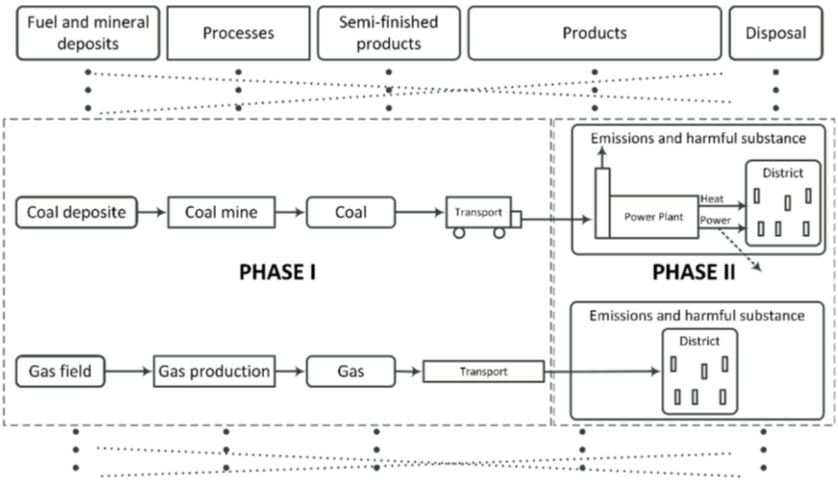

Figure 3. Interconnections between phases I and II in the TEC of entire life cycle

Table 6. Environmental impact of all elements present in phase I and II given for coal in major impact categories

Element of the system/type of material/substance/energy	TEC [MJ per year]
Pipeline	
Steel	1,940,072,349
Internal epoxy coating	1,826,107
The outer shell 3LPE	36,345,062
Concrete weight coating	18,553,979
Aluminium anodes	3,298,811
Zinc anodes	2,913,244
W2: Polyurethane	7,781,137
Rock material – gravel	2,658,195
Pumping stations	
The amount of energy in the pumping station at Portovaya	30,550,306,974
The amount of energy in the section to the Portovaya (20 stations)	16,694,156,817
Natural gas emitted from losses to the atmosphere (2%)	22,712,413,578

TEC is provided for j^{th} considered product the production of which consumes i^{th} domestic products, r^{th} imported products, direct exergy of s^{th} non-renewable resources and releases k^{th} harmful substance to the environment. The term j^{th} considered product consists of i^{th} domestic and r^{th} imported products that together define product range. From the set of equations indicators ρ_j, ρ_i and ρ_r are calculated; however, depending on the approach additional equations are needed in case of imported goods:

$$\rho_j + \sum_i \left(f_{ij} - a_{ij}\right)\rho_i = \sum_k p_{kj}\zeta_k + \sum_s b_{sj} \tag{8}$$

Results presented in tab. 4 also show that the pumping stations have strong influence on the TEC results. It should be noticed that the results are similar to the one presented in [13].

Conclusions

The results of the classical LCA suggests that the overall negative environmental impact related to the use of coal for heating purposes is higher for use of natural gas in all impact categories with the exception of ozone layer depletion.

The impact on climate change of both heating solutions is similar. The significant influence of transportation of natural gas should be underlined especially in 100 years time horizon. It is due to large leakage of methane from pipelines.

However, the localization of boilers in distributed heating system based on natural gas changes the situation in human toxicity impact category significantly. High population density in places where the emission takes place increases the real impact due to the high sensitivity of the area and large number of receptors. Additionally the emission from domestic heating boiler releases the emission without any fuel gas treatment devices. The situation with the coal-fired heating plant is different. The plant is located in the less populated area and as an effect fewer receptors are affected. That is why the devastating influence in human toxicity impact category is lower for coal use than natural gas use.

The results gained in this work could work as an argument in the discussion about fossil fuel based energy systems and their environmental impact.

Nomenclature

a_{ij} – coefficient of the consumption of i^{th} domestic product consumed in j^{th} considered branch, unit of i^{th} domestic product per unit j^{th} product, [kgkg^{-1}]

b_{sj} – direct exergy consumption of s^{th} non-renewable natural resource in j^{th} considered branch, MJ of exergy per unit of s^{th} non-renewable natural resource per j^{th} product, [MJkg^{-1}]

f_{ij} – coefficient of by-production of i^{th} domestic product per j^{th} product, unit of i^{th} by-product per unit j^{th} product, [kgkg^{-1}]

$\mathrm{LoC_{H,LCz}}$ – allocation coefficient for human toxicity on the stage of life cycle LCz, [–]

$\mathrm{LoC_{HT}}$ – location indicator calculated for the human health impact category, [–]

$\overline{\mathrm{PD}}$ – average population density in reference area, [–]

$\mathrm{PD_{LCz}}$ – population density in particular area (affected by the processes carried out during life cycle stage LCz), [–]

p_{kj} – amount of k^{th} waste substance released to the surrounding environment from j^{th} considered branch, kg of k^{th} harmful substance per j^{th} product, [kgkg^{-1}]

$\mathrm{SV}_{x,y}$ – sensitivity of cell x, y, [–]

$\overline{\mathrm{TASV}}$ – average (test area sensitivity value), [–]

$\mathrm{II_{HT,PHI}}$ – impact indicator in the human health impact category for the phase I without taking into account the location of the system, [–]

$\mathrm{II_{HT,PHII}}$ – impact indicator in the human health impact category for the phase II without taking into account the location of the system, [–]

$\mathrm{II_{HT,TOTAL}^{LoC}}$ – total impact indicator in the human health impact category for the life cycle (phase I and phase II) taking into account the location of the system, [–]

$\mathrm{II_{HT,PHII}^{LoC}}$ – impact indicator in the human health impact category for the phase II taking into account the location of the system, [–]

Greek symbols

ρ_i – thermo-ecological cost of i^{th} domestic product, MJ of exergy per unit of i^{th} domestic product, [MJkg^{-1}]
ρ_j – thermo-ecological cost of j^{th} considered product, MJ of exergy per unit of j^{th} considered product, [MJkg^{-1}]
ζ_k – thermo-ecological cost of k^{th} harmful substance rejected to the environment, MJ of exergy per kg of k^{th} harmful substance, [MJkg^{-1}]

Acronyms

IMM – immission matrix
LCA – life cycle analysis
RIMM – relative immission matrix
RIV – relative immission vales
TEC – thermo-ecological cost

References

[1] ***, EUROSTAT, Primary Production of Energy by Resource, 2016
[2] ***, BP Statistical Review of World Energy, June 2015, Coal Section, http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-coal-section.pdf
[3] Riva, A., *et al*., Natural Gas and the Environmental Results of Life Cycle Assessment, *Energy*, *31* (2006), 1, pp. 138-148
[4] Dinca, C., *et al*., A Life Cycle Impact of Natural Gas Used in the Energy Sector in Romania, *Journal of Cleaner Production*, *15* (2007), 15, pp. 1451-1462
[5] ***, BP Statistical Review of World Energy June 2015, Natural Gas Section, http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-natural-gas-section.pdf
[6] ***, Nord Stream ESPOO Report, the New Gas Supply Route for Europe, Chapter 04, Description of Project, 2009, https://www.nord-stream.com/download/document/74/?language=en
[7] ***, Gazprom, Information Publication, Yamal Megaproject, http://www.gazprom.com/f/posts/25/697739/book_my_eng_1.pdf
[8] Schreiber, A., *et al*., Environmental Assessment of German Electricity Generation from Coal-Fired Power Plants with Amine-based Carbon Capture, *The International Journal of Life Cycle Assessment*, *14* (2009), 6, pp. 547-559
[9] Pikon, K., Environmental Impact of Waste Management System – System Location Issues, World Environmental and Water Resources Congress, EWRI 2011, Palm Springs, Cal., USA, 2011, America Society of Civil Engineers ASCE, Conference paper
[10] Pikon, K., *Model of Multicriteria Environmental Evaluation of Complex Technological Systems* (in Polish), Wydawnictwo Politechniki Slaskiej, Gliwice, Poland, 2011
[11] Szargut, J., *Themodynamics* (in Polish), Version improved and supplemented, PWN, Warszawa 1991, Wydawnictwo Politechniki Slaskiej, Gliwice, Poland, 2000
[12] Stanek, W., *et al*., Thermo-ecological Cost of Hard Coal with Inclusion of the Whole Life Cycle Chain, *Proceedings of SDEWES Conference*, Venice-Istanbul, 2014
[13] Stanek, W., Bialecki, R., Can Natural Gas Warm the Climate More Than Coal? *Fuel*, *136* (2014), Nov., pp. 341-348

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