CHEMICAL ENGINEERING TRANSACTIONS
VOL. 42, 2014
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Neven Duić

ISBN 978-88-95608-33-4; **ISSN** 2283-9216
DOI:10.3303/CET1442024

Environmental Quality Evaluation of Hard Coal Using LCA and Exergo-Ecological Cost Methodology

Lucyna Czarnowska*[a], Wojciech Stanek[b], Krzysztof Pikoń[a], Jan Nadziakiewicz[a]

[a]Department of Technology and Installations of Waste Management, Silesian University of Technology, Gliwice, Poland
[b]Institute of Thermal Technology, Silesian University of Technology, Gliwice Poland
lucyna.czarnowska@polsl.pl

Abstract

The world's global economy is based on the access to energy. The majority of useful energy is still produced by combustion of fossil fuels that belongs to non-renewable natural resources. Besides the depletion of non-renewable resources there is also a problem related to release of waste substances into the natural environment. Moreover, efficient power and energy sector is one of the factors determining the competitive management of countries or regions. Often the improvement of energy management is focused on power technologies or effectiveness of final production processes. However, some improvement can be found in the stage of extraction, processing and transportation of fuels. To evaluate chains of the processes inside the system the ecological analysis such as Life Cycle Assessment (LCA) or Thermo-Ecological Cost (TEC) analyses is necessary. LCA in association with characterization factors is commonly used; however, TEC which is based on second law of thermodynamics is not so widespread. In the papers fundamentals of both TEC and LCA methods are described. The example results of TEC and LCA application in the case of extraction of hard coal from Polish coal mines are presented.

Keywords

Thermo-Ecological Cost, Life Cycle Assessment, non-renewable resources, exergy, coal mine, fuels.

1. Introduction

The present world's energy demand is still mainly covered by fossil fuels, i.e. petroleum, natural gas and coal. There are two global problems related to the use of the limited resources of fossil fuels – depletion of natural resources and environmental damage due to emissions of various substances such as, SO_x, NO_x, PM, CO_2 and others. Depletion of natural non-renewable resources, particularly fossil fuels, is accelerated by continuously increasing consumption. On the other hand, from the economic point of view the increase of consumption is also a base for further development of societies. However, such increasing development, which currently is based on limited resources, provides an ecological threat to the existence of future generations. It is predicted that in case of Polish economy the fossil fuels especially coal will be the basic source of electric power. Table 1 presents the expected structure of fuel consumption in the Polish power sector till year 2030 (Economy 2009), whereas the production of coal in Polish conditions is presented in Table 2 (CSO 2012a).The rapid development in some regions caused a sudden decrease of coal deposits; moreover, this dependence is reflected by proved reserves estimated in different years, which are assessed by BP (BP, 2013). There is a probability that such trends can appear also in the other fossil fuels. For this reason, all accessible efforts to slow down these processes should be applied. Also scientific methods for measure sustainability should be developed and commonly used together with the classical economic criterion.

Environmental risks associated with the growth of consumption can be divided into two groups: depletion of non-renewable natural resources and emissions. Environmental damages and losses caused by the

Please cite this article as: Czarnowska L., Stanek W., Pikoń K., Nadziakiewicz J., 2014, Environmental quality evaluation of hard coal using LCA and exergo-ecological cost methodology, Chemical Engineering Transactions, 42, 139-144 DOI:10.3303/CET1442024

release of waste substances from production processes can be evaluated using different impact categories which are used in classical Life Cycle Assessment (LCA) method (Pikoń 2012).The environmental impact can be expressed through Thermo-Ecological Cost (TEC) method, which take into account the depletion of non-renewable natural resources and compensation or prevention of these impacts. In order to reduce the consumption of non-renewable natural resources, the use of renewable ones should increase. The replacement of fossil fuels by biomass is a promising option for power technologies as well as for synthetic fuels production (Heijden and Ptasinski, 2012).

Table 1: Production of electricity in Poland based on fuel type structure, [TWh] (Economy 2009)

Energy source	2010	2015	2020	2025	2030
Hard coal	**68.2**	**62.9**	**62.7**	**58.4**	**71.8**
Lignite	44.7	51.1	40.0	48.4	42.3
Natural gas	4.4	5.0	8.4	11.4	13.4
Oil	1.9	2.5	2.8	2.9	3.0
Nuclear	0.0	0.0	10.5	21.1	31.6
Renewable energy sources (RES)	8.0	17.0	30.1	36.5	38.0
Other	1.6	1.6	1.6	1.7	1.7
TOTAL	**128.7**	**140.1**	**156.1**	**180.3**	**201.8**

Table 2: Production of different kind of fuel in Poland in the years 2008-2011, [Tg] (CSO 2012a)

Indigenous production	2008	2009	2010	2011
Steam coal	72,321	69,524	65,070	65,012
Coking coal	12,024	8,540	11,658	11,436
Lignite	59,668	57,108	56,510	62,841
TOTAL	**144,013**	**135,172**	**133,238**	**139,289**

LCA as one of the methods for environmental assessment analysis is officially included in standard ISO 14040 (ISO, 2006). LCA is a methodology to evaluate environmental impact and to identify the opportunity to improve environmental performances. It has emerged as a valuable decision-support tool for both policy makers and industry in assessing the cradle-to-grave impacts of a product or process. LCA produces some impact indicator in different impact categories. In recent times, when environmental issues have gained increasing priority with regard to the cost effectiveness of using one fuel rather than another, there is a constant interest to evaluate the environmental value of fuels considering their entire life cycle.

Many studies on the application of LCA methodology have been carried out to evaluate the environmental value of fuels and to have advanced techniques for the assessment of environmental performances of energy industry considering the complete life cycle of fuels including alternative ones. However**,** this method suffers some limitations. Although environmental impact assessment of energy production from fossil fuels is relatively easy - the valuation of the environmental properties of the fuel itself is more problematic especially without information where the fuel is combusted. The limitations and disadvantages lay also in difficulties in the comparison of results in different impact categories as well as in usage not objective functional units and boundary; however, these disadvantages are eliminated in the TEC.

The TEC is based on cumulative calculus and on second law of thermodynamics. The calculation of the cumulative coefficients was initiated by Chapman, who introduced the concept of energy cost (Chapman 1974). Nowadays, thermodynamic indicators of process performance based on the second law of thermodynamic and exergy concept are commonly accepted as the most natural way to measure the performance of different processes, ranging from energy technology, chemical engineering, transportation, agriculture, etc. The TEC expresses the cumulative consumption of non-renewable exergy of natural resources (Szargut 2005). The TEC method in comparison with other methods of ecological assessment can bring all environmental impacts to one metric which is the exergy of consumed natural non-renewable resources. The TEC method fulfils the requirement of LCA; moreover, the minimization of the TEC (Szargut and Stanek, 2009) ensures a mitigation of the depletion of non-renewable resources. To estimate the amount of clean fossil fuel resource, the abatement cost can be used (Valero and Valero, 2012).

The objective of this study is to provide the TEC of products, which burden the hard coal extraction, based on the Polish statistical data of material (CSO 2012a) and energetic (CSO 2012b) supplies. The TEC results of hard coal will concern the energy carrier and material supplies. Moreover, the results of both TEC and LCA analyses will be presented.

2. Methodology description

2.1 Life cycle assessment

LCA, which has been developed for evaluating the impacts of technical processes and products on the environment, is a systematic analytical method that helps identify, evaluate, and minimize the environmental impacts of a specific process or competing processes. Material and energy balances are used to quantify the emissions, resource consumption, and energy use of all processes between the transformation of raw materials into useful products and the final disposal of all products and by-products. Then, the results are used to evaluate the environmental impacts of the process so that efforts can be focused on mitigating possible effects. LCA produces some impact indicator in different impact categories.
In the case of hard coal extraction from coal mines, three characteristic phases (Czaplicka-Kolarz 2002), such as 1) providing and preparing the deposit for exploitation, 2) the exploitation of coal deposits, 3) decommissioning of the mine, should be taken into account during LCA analysis. Moreover, the impact categories presented in Figure 1 are important from the extraction of hard coal deposits.

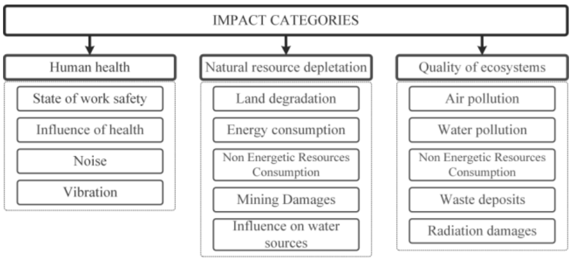

Figure 1: Impact categories of a coal mine on the natural environment (Czaplicka-Kolarz 2002)

The exemplary life cycle inventory of the emission from the coal used in electricity production system is presented in Babbitt and Lindner, 2005. It is important to indicate that the emission and other environmental, social and economic issues (Azapagic, 2004) occur on each phase of the coal life cycle starting from the raw coal extraction thought the associated processes, coal combustion up to disposal.

2.2 Thermo-ecological life cycle assessment

The contemporary problems related to the depletion of non-renewable resources become more and more important taking into the account growing level of worldwide consumption. For this reason, the classic economy should be supplemented with a method based on a physical phenomenon and taking into account the influence of human activity on the depletion of natural resources (Szargut 2005). Moreover, it is important from the point of view of sustainable development. Additionally, the whole life cycle of a product should be analysed. The TEC (Szargut 2005) fulfils the requirements mentioned above; furthermore, it can be applied for optimisation that leads to minimisation of depletion of natural non-renewable resources. The TEC is defined as (Szargut 2005) “cumulative consumption of non-renewable natural resources with inclusion the necessity of compensation of the negative effects of rejection harmful wastes of the natural environment”. The index of TEC can be calculated from the balance of cumulative exergy:

$$\rho_j+\sum_i (f_{ij}-a_{ij})\rho_i-\sum_r a_{rj}\rho_r=\sum_f b_{fj}+\sum_m b_{mj}+\sum_k p_{kj}\zeta_k \qquad (1)$$

where ρ_j, ρ_i, ρ_r are total value of the TEC of major product of the j^{th} considered process, of the remaining processes belonging to the system and of the r^{th} imported product, b_{fj}, b_{mj} *are* exergy of the fuel and of the mineral raw material immediately extracted from nature, per unit of the j^{th} major product, a_{ij}, a_{rj} are the coefficient of the consumption of the i^{th} domestic and r^{th} imported semi-finished product per unit of the j^{th} major product, f_{ij} is coefficient of the production of the j^{th} by-product per unit of the j^{th} major product, p_{kj} is coefficient of the production of the k^{th} rejected waste product per unit of the j^{th} major product, ζ_k is total TEC of compensation of the deleterious impact of the k^{th} rejected waste product.
The total value of TEC_j of the products of production j^{th} branch results first of all from direct consumption of non-renewable exergy b_{si}. Additionally, the TEC_j results from consumption of raw-materials, semi-finished products a_{ij} and imported goods a_{rj} with known TEC index. The product of branch “*j”* has to be burdened with the TEC resulting from the rejection of harmful substances to the environment. If the j^{th} branch is multi-product branch, the TEC should be decreased by thermo-ecological cost of all by-products f_{ij}. The detailed description of balance method with example calculations is given in (Stanek 2009). The balance equations

are mutually dependent if some useful product is applied as a raw material in another production process. Because the non-renewable fossil resources can be generally divided into mineral (material) and chemical (fuels/ energy carriers) the TEC can be also decomposed in such a way (Szargut and Stanek 2012). The calculation of the fuel TEC_f and mineral TEC_m can be done in two steps. In the first one the general form of the balance equations determining the total TEC has to be formulated including total fuel and mineral non-renewable exergy. In the second step the balance equations may be formulated that contain the unknown fractions z_j, z_i of the fuel TEC_f in the total value of TEC. The first system of the mentioned balance equations determining the total TEC, and the values of ρ_j, ρ_i are unknown. The second system of balance equations, which is independent from the first one, determines the fuel part of TEC:

$$z_j\rho_j + \sum_i (f_{ij} - a_{ij}) z_i \rho_i - \sum_r a_{rj} z_r \rho_r = \sum_f b_{fj} + \sum_k p_{kj} z_k \zeta_k \quad (2)$$

The values of z_j, z_i are unknown in the second equation systems. In Eq(1) and Eq(2) the components with b_f, b_m appear only when considering the mines extracting raw materials from nature.

The total cost of energy consumption is not only burdened with the conventional cost, but also with the external cost (expressed in monetary units or physical units). The last part of both Eq(1) and Eq(2) contains the additional expenses of cumulative exergy of non-renewable resources arising from the formation of waste products within the j^{th} production process. Determination of the exergetic cost of compensation ζ_k is one of the most difficult tasks in the determination of (TEC). In (Szargut 2005), the simplified method based on the knowledge of externalities expressed as monetary indices of harmfulness is proposed. The average external monetary costs w_k resulting from combustion of fuels in Polish conditions is presented in Table 3. Moreover, the external cost w_k of pollution (Szargut 2005) can be used to determine the influence of a particular pollutant on the depletion of natural resources by means of thermo-ecological cost expressed in physical units. Additionally, the thermo-ecological cost of abatement can be also obtained. These three indicators are presented in Table 3 for SOx, NOx and PM; however, in case of CO_2 emission only the TEC abatement is presented since CO_2 does not cause the direct influence on the environment. The external cost of emission is presented in (Czarnowska and Frangopoulos 2012).

Table 3: Comparison of different approaches of externalities

Environmental indicator	Symbol	Unit	CO_2	SO_x	NO_x	PM
External monetary cost	w_k	€/kg	-	12.81	9.41	7.00
TEC of waste substance	ξ_k	MJ/kg	-	97.82	71.88	53.42
TEC abatement	σ*	MJ/kg	4.40	17.50	26.00	0.50

3. Results

Table 4 and 5 present the material and energy balances for the coal mines in Polish conditions. The presented data for the years 2008-2011 represent the set of input data for both 1) life cycle assessment, 2) thermo-ecological cost analyses of coal mine extraction. Moreover, the obtained TEC results, which are presented in the last column, are mainly based on presented Polish statistical data.

The climate change categories, which is the second impacts presented in Table 6, is equal to 66.9 kg CO_2eq/Mg of hc; whereas the emission of CO_2 from combustion of coal is equal about 2200 kg CO_2/Mg of hc; it means that the external LCA climate impact is equal about 3.2% of combustion one. It indicates, that the CO_2 emission in full life should not be neglected taking into account the level of coal production in Polish conditions (see Table 2). One of the possibilities to decrease this factor is the utilization of methane from coal beds. It would lead to multiple of positive effects because: 1) instead of CH_4 emission the CO_2 emission is released to the atmosphere, 2) the by-products as electricity and useful heat or coal are generated that should lead to further decrease of indices in all categories included in Table 4. It should be noted that 1 kg of CH_4 influence the global warming about 30 times more than the CO_2.The LCA and TEC results of Polish hard coal, which are presented in Table 6, are divided into energetic and material part. The first part – energetic one – results from the consumption of energy carriers in coal mine, which is presented in Table 4 (columns 2-5). The second part – material one – results from the consumption of all materials presented in Table 5 (columns 2-5). Presented values of both parts (Table 6, last row) covers the whole life cycle chain leading to fabrication of particular material and energy carrier. In all impact categories of LCA as well as in TEC, the contribution of energetic part is dominating one. This share varies from 0.803 for human toxicity up to 0.989 in the category of acidification potential. The obtained results indicate, that from the point of view of improvement of ecological effectiveness of hard coal mine, the energy subsystem should be examined firstly. The presented results indicate that for rationalization of energy and environmental management of hard coal extraction the application of TEC is sufficient.

Table 4: Energy carriers consumption in hard coal mines in Poland in the years 2008-2011 [TJ/total production of hard coal] (CSO 2012a) and their thermo-ecological cost

Energy carriers inputs	2008	2009	2010	2011	TEC
Steam coal	13,424	8,576	2,104	2,012	1.31
High - methane natural gas	407	494	809	877	1.15
Peat and wood	0	87	57	39	0.01
Motor gasoline	22	18	19	18	2.08
Automotive diesel oil	456	484	560	602	1.24
Light fuel oil	21	23	37	22	1.65
Coke oven gas	136	126	142	144	1.92
Electricity	15 461	15 291	15 669	15 550	4.72
Heat	4 279	4 542	5 108	4 299	2.29

Table 5: Selected material consumption in hard coal mines in Poland in the years 2008-2011 [Mg/total production of hard coal] (CSO 2012b) and their thermo-ecological cost [MJ_{ex}/kg_i]

Material inputs	2008	2009	2010	2011	TEC
Coniferous sawn wood	13,785	33,741	29,522	27,351	23.68
Total (hard) fibreboards	2,370	2,428	1,016	859	53.51
Particle boards	123	152	142	148	39.84
Paper and paperboard	239	300	206	167	50.67
Sodium hydroxide	55	30	71	59	18.32
Cement	4,972	10,338	7,619	3,547	3.66
Lime	573	461	524	867	4.10
Building paper	19,585	15,944	10,256	7,001	71.56
Sheets and other hot rolled products (excluding semi-finished products)	10,348	15,510	8,521	8,797	30.46 - 35.38
Cold rolled steel sheets	164	59	37	19	35.38
Tin-planted sheets and strips	31	23	11	10	35.75
Zinc coated sheets and strips	34	32	20	15	35.71
Steel wire (drawn)	200	151	82	70	32.50
Steel tubes	10,715	10,961	8,859	8,146	32.91

Table: 6 LCA and TEC results of Polish hard coal mines

No.	LCA impact categories/ TEC	Units	Material Part	Energetic Part	Total	Contribution of fuel in total
1	Acidification potential	kg SO_2-eq/Mg hc	0.004	0.350	0.354	0.989
2	Climate change	kg CO_2-eq/Mg hc	0.955	65.930	66.885	0.986
3	Eutrophication potential	kg phosphate-eq/Mg hc	0.003	0.128	0.131	0.979
4	Human toxicity	kg DCB-eq/Mg hc	1.270	5.191	6.461	0.803
5	Abiotic depletion	kg Sb-eq/Mg hc	0.012	0.597	0.609	0.980
6	Ozone layer depletion	kg R11-eq/Tg hc	0.091	1.588	1.679	0.946
--	**TEC**	**MJ exergy/MJ hc**	**0.034**	**1.209**	**1.243**	**0.972**

hc – hard coal

The basic disadvantages of LCA analysis are some difficulties in results comparison. The LCA analysis consists of various impact categories, six of them are chosen and presented in Table 6. To omit this issue some weighting factors, that are dependent on the preferences of the decision makers, are used. The disadvantages of the existence of different impact categories are eliminated in the case of TEC analysis, since all impact are expressed with one unit measure, which is the cumulative consumption of non-renewable exergy of natural resources (exergy). This is the advantages of TEC method in comparison with LCA.

4. Summary and conclusion

In this article, the practical example of ecological evaluation of extraction Polish hard coal is presented. Both LCA and TEC methods are used to show the environmental impact of Polish hard coal mining. In Poland, the various types of coal are extracted, the structure is 50% steam coal, 43% lignite and 7% coking coal (see Table 2). Moreover, the electricity in Poland is mainly produced from coal and this trend will not be significantly changed (see Table 1).

In the hard coal mine during the analysed years, the consumption of steam coal decreased 7 times, while the consumption of methane increased twice, when other energy carriers remained unchanged. Sometimes, the peat is reported; however, the TEC of peat is very low, so it could be omitted in the analysis. The largest TEC in the case of energy carriers is for electricity (see Table 3), and finally, it mostly burdens the TEC of extracted coal.

The value of the TEC for the materials is in the range from 3.66 MJ_{ex}/kg of cement to 71.56 MJ_{ex}/kg of building paper (see Table 4). Despite such large TEC of some minerals, the used quantities do not lead to a significant increase in total TEC of hard coal.

All LCA indices as well as the TEC indicate that energetic part much more burden the hard coal extraction than the mineral part. In the case of LCA indices, it is difficult to determine which effect is more environmentally damaging, for this reason the weighing factors should be used. In this work, the weighting factors are not taken into account. The TEC is comprehensive indicator, which represents the total environmental impact. The average TEC is equal 1.243 MJ_{ex}/MJ of hard coal extracted in Poland.

To sum up, both methods should be integrated to achieve comprehensive tools for ecological assessment of any production system. The share of the material part of both LCA and TEC is significantly lower than the energetic part. As the results show the analysis of primary energy extracting processes, which mainly means the energy sub-system, should be firstly analysed to find the potential improvement of the overall system.

Acknowledgements

The paper has been prepared in the frames of the project: "Development of an expert system for assessment of environmental, economic and social performance of coal mines in Poland", funded by the National Centre for Research and Development under the Applied Research Programme.

References

Azapagic A., 2004. Developing a framework for sustainable development indicators for the mining and minerals industry. Journal of Cleaner Production, 12, 639-662, DOI: 10.1016/S0959-6526(03)00075-1.

Babbitt C.W., Lindner A.S., 2005. A life cycle inventory of coal used for electricity production in Florida. Journal of Cleaner Production, 13, 903-912, DOI: 10.1016/j.jclepro.2004.04.007.

BP, 2013. Statistical Review of World Energy., <eugbc.net/files/4_138_612959_ BPStatisticalReviewofWorldEnergy-Brussels,September2008.pdf> , accessed 21.09.2014

Chapman P.F., 1974. Energy costs: a review of methods. Energy Policy 2, 91–103.

CSO, 2012a. Energy statistics 2010-2011. Central Statistical Office, Warsaw, Poland.

CSO, 2012b. Materials management 2011 Central Statistical Office, Warsaw, Poland.

Czaplicka-Kolarz K., 2002. The use of life cycle assessment (LCA) in ecobalances of mines: a collective work (in Polish). Główny Instytut Górnictwa, Poland.

Czarnowska L., Frangopoulos C.A., 2012: Dispersion of pollutants, environmental externalities due to a pulverized coal power plant and their effect on the cost of electricity. Energy, 41, 212-219.

Economy, 2009. (Ministry of Economy) Energy Policy of Poland till 2030 (in Polish), Warsaw, Poland

Heijden H., Ptasinski K., 2012: Exergy analysis of thermochemical ethanol production via biomass gasification and catalytic synthesis. Energy, 46, 200–210, DOI: 10.1016/j.energy.2012.08.036

ISO, 2006. ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework, International Standard Organisation,, <www.iso.org/iso/catalogue_detail?csnumber= 37456>, accessed 21.09.2014

Pikoń K., 2012. LCA as a tool in sustainable development policy introduction. Archiwum Gospodarki Odpadami i Ochrony Środowiska, 14, 55-63.

Szargut J., 2005. Exergy method: Technical and ecological applications. WIT Press, Boston, US.

Szargut J., Stanek W., 2012. Fuel part and mineral part of the thermoecological cost. International Journal of Thermodynamics, 15, 187-190.

Valero A., Valero A., 2012. What are the clean reserves of fossil fuels? Resources, Conservation and Recycling, 68, 126–131, DOI: 10.1016/j.resconrec.2012.08.004.