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Thermo-ecological cost of hard coal with inclusion of the whole life cycle chain

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ABSTRACT

Fossil fuels are still the dominant source of energy in most economic sectors worldwide, particularly in the electric power sector. The transformation and usage of primary energy are connected with various unfavorable environmental effects. Mainly they are as follows depletion of constrained resources of non-renewable energy, emission of harmful wastes to the environment, emission of GHG (greenhouse gasses). To investigate these effects variety of methods have been developed, the LCA (Life-Cycle Assessment) is one of them. 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. Despite many advantages of LCA, it is unfortunately characterized by the lack of inclusion of thermodynamics law, especially second law, which is the basic physical law deciding on the resource economy in any production process. In the paper, the LCA methodology together with TEC (Thermo-Ecological Cost) is proposed to apply for exergo-ecological evaluation of fossil fuels. TEC expresses the cumulative consumption of non-renewable exergy connected with the fabrication of any useful product with additional inclusion of the consumption resulting from the necessity of compensation for environmental losses caused by the removal of harmful substances to the environment. The calculations of TEC of coal are based on the material balances of the whole chain of the production process from mine to the end-user. Within the chain in the coal mine the following sub-processes have been distinguished: preparation of the coal deposit layer for exploitation, exploitation of coal deposits, mechanical processing and enrichment of coal, ventilation of coal mine, transport, energy management of coal mines, compressed air management in coal mines and utilization of methane released during mine exploitation. Besides the processes in the mine, the end use is investigated. For this reason, the different types of coal are assigned for typical users. The potentially negative influence of utilization of coal with inclusion from cradle to grave assessment are examined on the basis of TEC evaluation.

1. Introduction

Primary energy in the form of fossil fuels dominates in the structure of the present world's energy demand [1]. Probably for years the worldwide economy will continue to base on the constrained non-renewable resources of primary energy. Moreover, the depletion of these resources is constantly accelerating by global trends in consumption growth. On the other hand, from the economic point of view the development of societies causes the increase in goods consumption [2]. However, such increase in development, which is currently based on limited resources, provides an ecological and further economic threat to the existence of future generations. In general, two global environmental problems related to the usage of the limited resources of non-renewable fossil fuels can be distinguished 1) depletion of natural resources and 2) environmental damage due to emissions of various substances. The estimated lifetime of fossil fuels and the changes of this estimation through years are presented in Fig. 1; it is based on data published by BP [1].

It is predicted for the Polish economy that the fossil fuels, especially coal, will be the basic source of electric power in the horizon of 2030. It should be noted that Polish energy sector is mainly based on steam power plants fed with hard coal and lignite [3]. Table 1 presents the expected structure of fuel consumption in

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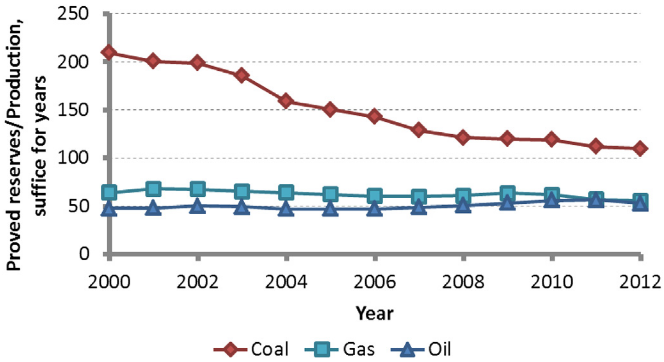

Fig. 1. Proven sufficient reserves estimated in different years [1].

the Polish power sector up to 2030 [4]. It seems evident that in the near future the coal will still play the dominant role as an energy source for electricity generation, for which the consumption demand increase due to the continous human development [2].

Damages and losses caused by the release of waste substances from production processes are one of the environmental risks associated with the increase of goods consumption. The environmental evaluation of waste substance can be obtained using LCA (Life Cycle Assessment) [5] or TEC (Thermo-Ecological Cost) method [6]. LCA is one of the well-known and commonly used methodologies for estimating complex environmental impacts of production systems. Detailed description of the idea, which is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, and the appropriate procedures for the assessment is presented in ISO 14040. In classical LCA, harmful substances are evaluated using different impact categories, the comparison of the assessment results is troublesome since weighting factors expressing the importance of particular impact category are not objective. In other words, the final conclusions from classic LCA can be subjective depending on the weighting factors used during the normalization stage. It should be noted, that damages and losses caused by production processes can be also expressed by the impact on the depletion of non-renewable natural resources. This more objective evaluation is possible using TEC method, in which compensation or prevention of these damages takes into account the additional consumption demand of natural resources. Connecting the databases of LCA with the theory of TEC creates the powerful tool to measure the sustainable development. In this case, the sustainability is expressed as the influence of production processes chains on the depletion of limited non-renewable resources.

The theory of Thermo-Ecology is based on both cumulative calculus and the second law of thermodynamics. The calculation of the cumulative coefficients was initiated by Chapman, who introduced the concept of energy cost [7]. Nowadays, thermodynamic indicators of process performance based on the second law of thermodynamic and exergy concept are commonly accepted for determining the efficiency of different processes, starting with the energy technology through chemical engineering, transportation, agriculture, etc.[6]. Szargut was the first who extended the exergy analysis from a single process to the entire production chain by proposing the important concept of CExC (cumulative exergy consumption) [8]. Subsequently, the concept of the TEC (Thermo-Ecological Cost) was evaluated, which enables the applications of exergy analysis in the field of environmental aspects. The TEC expresses the cumulative consumption of a non-renewable exergy of natural resources burdening the fabrication of useful products [9].

Ecological application of exergy can be widely found in the literature. Frangopoulos proposed environomics analysis, which takes exergy, economic, and environmental aspects into evaluation and optimization of energy systems [10]. However, this method does not take into account the cumulative exergy that is important to investigate the whole cycle from the cradle to grave. Sciubba proposed the concept of extended exergy accounting, in which input of resources supplemented by human labour aspects is included [11]. Based on [11] the exergetic evaluation of production systems including societies is developed. Moreover, the abatement cost and exergy evaluation of water resources are discussed in details in Ref. [12].

The calculations of TEC of coal within the entire life cycle is presented in this paper. The presented results show the practical applicability of TEC within ecological evaluations.

Majority of papers devoted to the ecological applications, which are based on exergy analysis, take into account a partial influence of production systems on the global environment. The methodology, which is presented in this paper, is the concept proposed by Szargut [9] and can be used as a common measure of ecological effects within the whole life cycle of any final product. It has to be underlined that in the TEC method all impacts are brought to the common denominator which is the depletion of non-renewable resources. The applied method can be also used as a measure of sustainability in terms of non-renewable depletion. The TEC theory with practical application have been presented so far in Ref. [18]. That paper presented the calculation results for selected production branches of domestic economy basing on their simplified input–output models. In the paper [13] the combination of TEC with detailed mathematical modelling has been presented. In the mentioned paper the authors presented the application of TEC to optimize the single purpose process (solar collector system) including the whole life cycle analysis. In the [19] it was proposed to apply the TEC for the determination of the pro-ecological tax that can be used e.g. as supporting tool for system fed with renewable energy and can replace the existing subsidizing systems. The next application of TEC [20] has been devoted to evaluation of the multi-generation system fed with both – renewable and non-renewable energy sources. In that paper the possibility of integration of thermo-economic and thermo-ecological analysis has been demonstrated. In this current paper the application of TEC coal mine representing the complex, multi-product industrial system is presented. The TEC analysis has been combined with the LCA assessment. The latter is used to generate the input data describing the fabrication of semi-finished products used both during the construction as well as during operation of coal mine. These data are combined with the real data from the example coal mine. The authors presented the modified TEC balance equation set that let to connect the LCA inventory analysis with the TEC procedure. As the coal mine is significantly responsible for methane emission the authors proposed the algorithm for evaluation of positive effects resulting from methane utilization as fuel for CHP (Combined Heat-and-Power plant) engines. The presented, comprehensive TEC

Table 1
Production of electricity in Poland based on fuel type structure, TWh [4].

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