PRACE NAUKOWE GIG
GÓRNICTWO I ŚRODOWISKO
Kwartalnik

RESEARCH REPORTS
MINING AND ENVIRONMENT
Quarterly 3/2010

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APPLICATION OF LCA IN FORESIGHT PROJECTS BASED ON THE EXAMPLE OF COAL ENERGY TECHNOLOGIES

Abstract

The paper aims to answer the question about the role of LCA in Foresight projects. Five clean coal technologies are under consideration: integrated gasification combined cycle with oxygen gasification and with air gasification, pulverized coal combustion with supercritical parameters, atmospheric circulating fluidised-bed boiler and oxy-combustion. The article compares results of assessments of above mentioned technologies by different methods: by experts in a foresight and based on calculations from LCA. Optimization of the technologies performed on the basis of different criteria showed that involving LCA is entirely appropriate and allows to accomplish impartial results because LCA unlike experts' analysis takes into account factors, which have considerable impact on natural environment.

Zastosowanie metody LCA w projektach foresight na przykładzie węglowych technologii energetycznych

Streszczenie

Projekty typu foresight mają na celu wyznaczanie kierunków rozwoju danej dziedziny oraz wsparcie dla procesów podejmowania decyzji politycznych w gospodarce, nauce lub finansowaniu badań, a metodyka foresightu jest wykorzystywana, między innymi w obszarze ochrony środowiska do oceny możliwości wdrożenia technologii przyjaznych środowisku. Jedną z metod wartych zastosowania w tego typu projektach wydaje się być metoda oceny cyklu życia (LCA). Celem artykułu jest analiza możliwości zastosowania oceny cyklu życia (LCA) w projektach typu foresight.

W ramach artykułu przeanalizowano pięć czystych technologii węglowych: układ IGCC ze zgazowaniem tlenowym oraz ze zgazowaniem powietrzem, kotły pyłowe na parametry nadkrytyczne, atmosferyczne kotły fluidalne z warstwą cyrkulacyjną oraz spalanie w czystym tlenie. Następnie porównano wyniki priorytetyzacji technologii z uwzględnieniem ocen eksperckich w zakresie bezpieczeństwa energetycznego i możliwości wdrożenia technologii, sprawności technologii, kosztów stałych i zmiennych oraz awaryjności technologii, jak również na podstawie wyników LCA.

Stwierdzono, że uwzględnienie w analizie eksperckiej wyników obliczeń metodą LCA spowodowało niewielkie, lecz zauważalne zmiany w rankingu technologii. Obliczenia metodą LCA uwzględniają czynniki, które mają istotny wpływ na oddziaływanie na środowisko, które trudno jest uwzględnić w ocenie eksperckiej. Z tego względu, włączenie LCA do etapu priorytetyzacji technologii w ramach foresightu jest jak najbardziej celowe i pozwala na uzyskanie pełniejszych i bardziej obiektywnych wyników.

INTRODUCTION

Technology foresight is a set of processes enabling multi-dimensional assessment of future trends in technology development on the basis of the current state of science, technology and social awareness as well as the links between them (Czaplicka-Kolarz,

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red. 2007b). In recent years, this methodology permitted to diagnose more frequently crucial, social and economic problems over various spans of time, it is also becoming an instrument of prognosing and decision making. In case of technologies dealing with energy safety, to which utilization of coal energy conversion belongs, is of particular importance.

The question, to which the authors of this article endeavour to find the answer, is: should the LCA of specific technologies be taken into consideration while determining critical technologies and their role in visions and foresight scenarios respectively? And if so, should application of multi-criteria optimization, including aspects of LCA and key factors determined by expects, take place and the results of this sort of analysis form a basis of further work performed by experts?
This article aims to answer the questions posed above.

1. USE OF LCA IN FORESIGHT PROJECTS

The objective of foresight projects is to determine directions of development in a given field as well as support for the processes of making political decision in economy, science or financing research. Foresight methodology is utilized among others in the sector of environmental protection for the assessment of environmentally friendly technologies. One of the methods worth implementing in these types of projects seems to be the Life Cycle Assessment (LCA) method.

Methods applied in foresight projects differ considerably from the LCA method. Foresight is used for very general assessment of technology based on general technological data, and it is aimed at creating a scenario or development strategy for the field under examination. The LCA, by contrast – is a very precise method, it refers to specific technology. The purpose of the LCA is to carry out an assessment of the influence on the natural environment based on accurate calculations referring to all processes, which take place in the whole life cycle of a given product or technological system, i.a. with respect to energy, material and raw material consumption. The analysis of life cycle is undertaken on the basis of currently existing technologies, whereas foresight methods refer to the future and are based on the probability of certain phenomena occurrence.

Notwithstanding the above mentioned difficulties, combination of these methods can be fruitful. The LCA method allows to determine which sphere of influence has the biggest significance in case of technology under examination – influence on natural environment (including acidification, eutrophisaction, photochemical oxidation, depletion of the ozone layer, greenhouse effect), influence on ecosystem (toxicity of seawater, fresh water as well as soil), or its effect on human health (toxicity, carcinogenic effect). Moreover, it allows to compare different technologies and products and choosing the most optimal one, but also to analyze the given technology with respect to possibility of introducing changes in order to improve its environmental impact. Within the works of STRATA as a result of the discussion held, the most important guidelines for assessment of environmental technologies in technological foresights were defined in PRECAUPRI project[1]. As a result, it was stated that the possibility of minimization or avoidance of negative impact on environment should be one of the most important assessment criteria. Furthermore, it was acknowledged that one of the most preferred methods of assessing impact on environment is the LCA.

In (Czaplicka-Kolarz, red. 2007a) the application of the LCA method in foresight projects was discussed, i.a.: Green Technology Foresight – 81 Options for the Environment[2], Danish Foresight about Environmentally Friendly Products and Materials (Green… 2005) and in the LCA project Perspective Life-Cycle Assessment on Wind Power Technology by 2020 (Dannemand, Bjerregaard).

In the first mentioned project, the influence of adopting systems of environment protection in various technologies on these processes efficiency and effectiveness was analyzed, and its aim was to motivate the decision-makers to actions fostering the development of more effective, environmentally friendly technologies. As a result of the analysis it was stated that 60 out of 81 environmentally friendly technologies have a positive influence on the efficiency of the process and the effectiveness of technology development. The assessment of its influence on environment has enabled the identification of technology development scenarios in macro-political and economic aspect. Combining foresight methodology with the LCA has made it possible to present the following findings, which could be the basis of political decisions:

- price regulation of fossil fuels is the biggest obstacle for high-performance, environmentally friendly energy systems,
- public and private scientific research, knowledge transfer and well-directed national policy should support the dynamic development of technology,
- price regulation by the government should support the possibility of existence of certain technologies in the market,
- supervision and intervention by the government should stimulate the development of environmentally friendly technologies.

The aim of the Danish project was to identify and assess chances and scientific and technological possibilities of environmentally friendly technologies in Denmark. The outcome was to identify spheres, in which innovative environmentally friendly technologies could become not only a solution for ecological problems, but also contribute to business, production and consumption development. In another Danish project, which was a continuation of the project described above, analysis of environment potential and the main environmental threats in the spheres of nanotechnology, biotechnology and information-communication technology was carried out. The project was i.a. directed at the analysis of future, innovative solutions in the sphere of environment protection. Using the LCA methods to assess future environmental aspects has shown a few crucial aspects, e.g. that influence on environment is not always related to a particular process or material, but is a result of the activity in its entirety. It has led to a conclusion, that complex legislative solutions during the processes of implementing new solutions are needed. Foresight has also shown, that the analysis of

[1] http://www.risoe.dtu.dk/rispubl/sys/syspdf/borup_paper.pdf (accessed 2.11.2009)
[2] Tamże.

positive and negative aspects of influence on environment enables to find solutions to the problems in their initial stage, and also allows to create and adopt optimal technological development scenario in accordance with the rules of sustainable development.

The aim of another Danish project utilizing LCA in technology foresight for the wind power plants assessment was the analysis of wind turbine impact at the production and disassembly stages in a long term as well as determining currently available possibilities of waste disposal. In the project, LCA of existing wind power plants as well as future systems was conducted. The LCA results have shown, that end of turbine's life is worth particular attention – disassembly stage and waste disposal, with which the biggest influence on environment is connected, and changes of applied materials should be taken into consideration in the future being analysed.

2. SELECTED MATURE AND EMERGING TECHNOLOGIES IN COAL BASED POWER GENERATION

Technologies, which aim is to generate heat and/or electrical energy from coal, can be generally divided into two groups: technologies in which coal is directly combusted and technologies in which gas produced out of coal is utilized. The more detailed division of technologies based on hard coal and brown coal is to be found in Table 1.

Table 1. Division of technologies in coal mining industry

No.	Technology group	Technology type
1	Pulverised coal combustion	1.1 Moderate supercritical parameters
		1.2 Increased supercritical parameters
		1.3 Ultra-supercritical steam parameters
2	Fluidised bed combustion	2.1 Atmospheric: under-critical and supercritical
		2.2 Pressurized (PFBC)
		2.3 With circulating fluidized bed (CFB)
3	Integrated coal gasification combined cycle (IGCC)	3.1 Air-blown gasification
		3.2 Oxygen-blown gasification
		3.3 Partial gasification: GPCCC, A-PFBC, GFBCC
		3.4 IGFC units with fuel cells
4	Oxy-combustion	4.1 New units
		4.2 Retrofit
		4.3 CRB Oxy-combustion
5	Chemical Looping O_2 and CO_2	5.1 Coal combustion with the use of chemical looping as O_2 carrier
		5.2 Coal gasification with the use of chemical looping as O_2 and CO_2 carriers

For further analysis with LCA and foresight method, five energy technologies were selected, which seem to be most significant: integrated gasification combined cycle IGCC with oxygen gasification and air gasification, pulverized coal combustion with supercritical parameters, atmospheric circulating fluidised-bed boiler as well as oxy-combustion. A short discussions of selected types of technologies are presented below (Czaplicka-Kolarz, red. 2007a; Szlęk et al. 2009).

Pulverized coal combustion with supercritical parameters

Owing to supercritical parameters of steam, in pulverized-fuel boilers with supercritical parameters, improvement of water circulation in power plant is obtained. However, hydrodynamics of steam-water cycle in such boiler differs considerably from traditional boiler and high temperature stresses can occur. For the construction of boilers creep-resisting, ferrite- martensitic and austenitic types of steels are used. Parameters of steam amount to around 25 MPa and 600°C. Further development aimed at attaining temperature of 700°C and 37.5 MPa will depend on the progress in the field of materials engineering. Hitherto, the largest in Poland once-through unit supercritical CFB boiler with supercritical steam parameters of 460 MWe (Foster Wheeler) is installed in Lagisza power plant.

Power units with fluidised bed

Technologies of combustion in fluidized bed are distinguished by flexibility in comparison with fuel – substantial amount of the deposit in a boiler causes that changes of fuel properties, such as calorific value, moisture or ash content do not cause either changes of combustion temperature or changes of generated heat flux. Co-firing of various types of fuel as well as using fuels of low calorific value is possible. Additional advantage of CFB boilers is lower amount of damaging pollutants emitted into the atmosphere. Its disadvantage is lower absolute efficiency in comparison with pulverized-fuel boilers, however, it is possible to obtain lower temperature of exhaust gas outlet. Mineral of the deposit in fluidised bed consists of limestone, which captures sulphur in the combustion process. Due to the use of air with oxygen depletion at the first stage of combustion, and then combustion of gas, occurrence of nitrogen oxide is avoided and steady temperature distribution in the chamber is obtained. Fluid technology, as a technology compliant with BAT, is recommended in the EU reference materials for large combustion sources.

Integrated gasification combined cycle (IGCC)

In IGCC, coal gasification is used in order to generate gas, which main components are hydrogen and carbon monoxide. Gas can be utilized as a biomaterial for chemical synthesis or can be combusted in a gas turbine in order to generate electrical and thermal energy. Composition and quality of generated gas are dependent on gasification medium, conditions in which reaction is carried out, composition and quality of fuel. Gasification medium can be air (air gasification) or oxygen (oxygen gasification). In the IGCC, gas generated out of coal after dedusting and desulphurization is combusted in gas turbine. In generator the energy of hot exhaust gas is used to produce electrical energy, and then in HRSG waste heat of the gas generates steam, which drives a steam turbine interconnected with separate electric generator. There are many IGCC systems in the world. The technology is believed to be interesting and it is developed fast. Pollutants are removed before gas is combusted in a turbine, and during combustion there is less emission generated.

Oxy-fuel combustion

Unlike conventional combustion technologies, instead of air, oxygen from air separation unit is supplied for combustion. Due to combustion in oxygen, waste gas contains hardly nitrogen, that is why carrying out sequestration of carbon dioxide is much easier. CO_2 included in waste gas is partially recycled and mixed with oxygen for combustion so as to avoid quick corrosion of the devices. Technology is at the stage of pilot plant of the power of a few MW. In the year 2008, pilot power plant Vattenfall, Schwarze Pumpe of the power 30 MW with CO_2 trapping was commisioned. Considerable influence on technology has the development of technology of producing pure oxygen.

3. METHODOLOGY OF TECHNOLOGY FORESIGHT IN COAL BASED POWER GENERATION

Primary energy consumption as well as requisite minerals consumption in technological process and emissions of harmful substances are not the sole subject of technology assessment. These factors are extremely important because of their influence on the environment. However, for experts use of LCA constitute only one element of detailed analysis of the technology and developing scenarios of technological development in a given field. To what extent does this element become substantial in case of the technology of energy efficient use of coal?

Experts working on the project of *technology foresight* aim to examine possible, probable and preferred versions of the future. On the basis of their knowledge they should envisage long-term technological solutions and define key technologies. Interactive and requiring commitment from various participants method of discussion and analysis, allows the assessment of likelihood and threats connected with implementing particular technologies. Experts formulate strategic visions, identify actions which need to be taken in order to develop technology and finally formulate the development scenarios.

Foresight always conveys the vision enclosed in the scenario description.

For *future* technologies (which are at present at their research stage, for which prototype systems do not exist, but they are being developed and implemented), *prototype* (which are not utilized, but we are dealing with the stage of prototype system construction, in case of which their weaknesses and ways of eliminating them are known) and *industrially mature* (technologies employed at present, whose further use is well-founded) – a list of technologies along with SWOT/STEEP analysis is achieved.

Prioritization of such a list of technologies is based on its limiting to critical technologies fulfilling the applied criteria to the greatest extent. With respect to technologies of energy efficient use of coal, to such criteria belong: ensuring energy safety and possibility of implementing technology. Technologies, which achieve good rating of both parameters of the assessment become candidates for the final list of *critical technologies*.

Key factors are those, which combine in itself the interaction force with a great deal of correlation, indicating, which actions should be considered as a priority in the process of technology development. The group of key factors consists of i.a. costs, failure risk, safety and the possibility of implementing technology itself, social acceptability etc. On the basis of key factors and their envisaged behaviour, a few options of development of the background environment are then created. Each option encompasses the same list of key factors. The difference between options comes down to diverse behaviour of individual factors. The most feasible options are then used in further formulation of development scenarios of technological advancement.

Key technologies applied simultaneously create one by one visions of sector's development, and in combination with key factors – scenarios. In this way, methodology of technology foresight applied in various projects of similar type can be outlined briefly (Czaplicka-Kolarz, red. 2007a, 2007b, 2008a, 2008b; Turek, red. 2008).

In case of technology of energy-efficient use of coal, experts were asked for an assessment of the technology in context of ensuring energy safety; moreover, they were asked for estimation of the possibility of implementation (or of further existence) of these technologies in Poland. What is more, experts took power efficiency, fixed and variable costs of the technology and energy consumption for own purposes into account and also estimated failure frequency of the technology.

Results of the assessment (as arithmetic mean of ratings of about 30 experts) are shown in Fig.1.

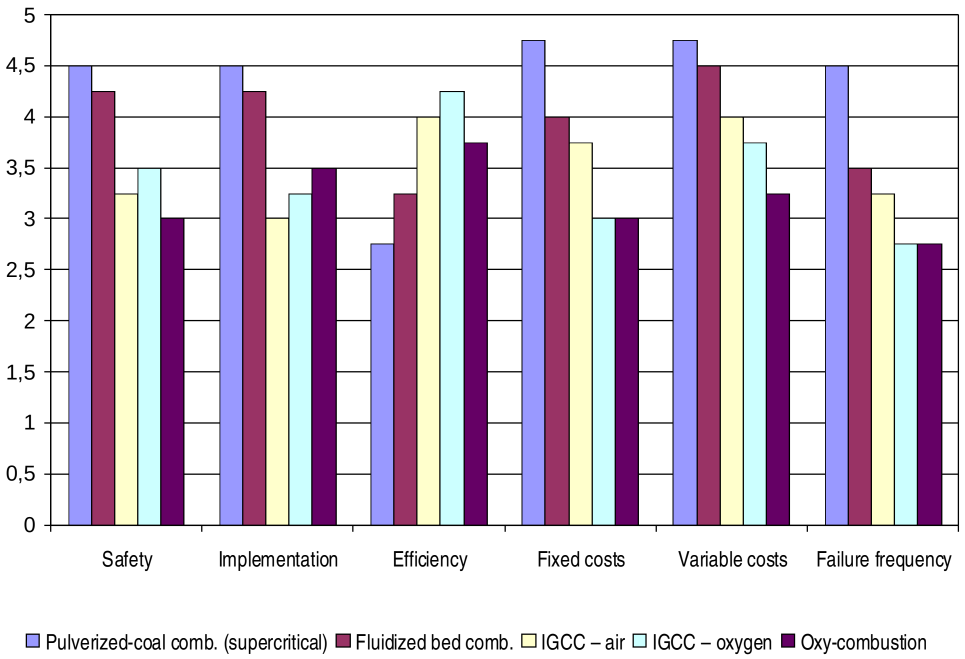

Fig. 1. Results of technology assessment by experts

Rys. 1. Wyniki oceny eksperckiej technologii

Assuming equal importance of key factors, in experts' opinion the highest total evaluation achieved combustion in atmospheric circulating fluidized bed (ACFB). Subsequent places in the rating were taken by: integrated gasification combined cycle with air gasification IGCC-air, integrated gasification combined cycle with oxygen gasification IGCC-oxygen, oxy-combustion and pulverized coal combustion with supercritical steam parameters.

4. LCA OF SELECTED CLEAN COAL TECHNOLOGIES

Life cycle assessment for selected five technologies of power generation was carried out with the use of Sima Pro programme. The functional unit was 1 GWh of generated energy. The fundamental input and output elements for analyzed technologies are juxtaposed below (Table 2).

Table 2. Selected input and output mass flows of clean coal technologies

		Unit	IGCC oxygen	IGCC air	Pulverized coal combustion (supercritical)	Fluidized bed combustion	Oxy-combustion
Input elements	Coal	Mg	372.00	432.15	379.35	161.19	392.9
	Electrical energy	MWh	123.02	121.9	0.06	1.00	
	Water	Mg	107.25	199.94	2.243		2199.2
	Absorber	Mg	20.45	15.32	38.53	5.08	
	Oxygen		2100 m^3				806.4 Mg
Output elements	Electrical energy	GWh	1.00	1.00	1.00	1.00	1.00
	CO_2 emission	Mg	340.66	411.41	763.26	288.48	84.6
	SO_2 emission	kg	41.79	0.23	0.19	0.24	
	NO_x emission	kg	151.42	0.16	0.59	0.29	300.8
	CO emission	kg	135.68	0.48			
	Emission – dust	kg	35.55	0.04	0.03	0.08	30.1
	Sewage	Mg	101.35	191.28	382.47		
	Solid waste	Mg	50.96	48.72	30.72		30.1

Table 3. Calculated environmental impact of selected technologies [Pt]

Impact category		IGCC oxygen	IGCC air	Pulverized coal combustion (supercritical)	Fluidized bed combustion	Oxy-combustion
Human health	Carcinogenicity	454.00	22.20	19.10	5.87	430.51
	Respiratory problems – org.	3.32	0.23	0.24	0.06	5.71
	Respiratory problems – non-org.	1750.00	–625.00	1780.00	1280.00	4900.20
	Climate changes	2320.00	2270.00	4190.00	1580.00	2257.04
	Radioactivity	0.10	0.12	0.02	0.00	209.29
	Ozone layer depletion	0.97	0.08	0.07	0.02	2.76
Human health in total		4528.39	1667.62	5989.43	2865.95	7805.50
Ecosystem quality	Ecotoxicity	152.00	10.40	10.40	2.66	222.09
	Acidification	202.00	–33.40	286.00	150.00	486.45
	Soil utilization	76.30	6.01	8.38	1.86	1345.31
Ecosystem quality in total		430.30	–16.99	304.78	154.52	2053.84
Resources	Minerals	2.84	0.47	0.42	0.09	70.65
	Fossil fuels	4780.00	3460.00	3460.00	1210.00	6717.19
Resources in total		4782.84	3460.47	3460.42	1210.09	6787.84
TOTAL		9741.53	5111.10	9754.60	4230.60	16647.18

In the Table 3 results of LCA are presented. Magnitude of the impact of selected five technologies on natural environment in areas of human health, ecosystem quality and resource depletion is given in Ecopoints [Pt].

The biggest impact of combustion processes is observed in human health category, which is connected with climate changes, but also respiratory problems which stem from the presence of non-organic compounds. Resources depletion is the predominant impact of gasification processes, which is related to fossil fuel consumption (Fig. 2).

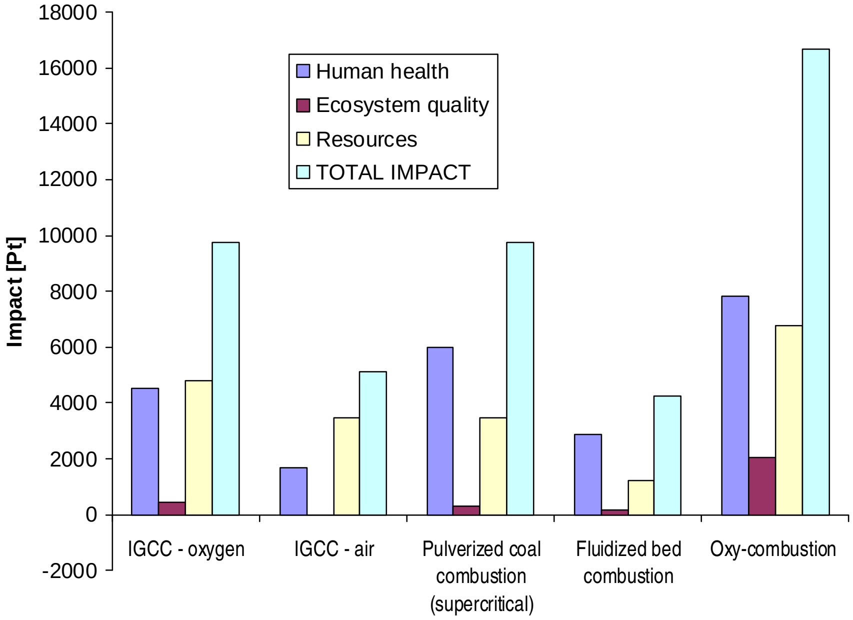

Fig. 2. Scale of impact on particular categories for selected coal technologies
Rys. 2. Wielkości oddziaływań w poszczególnych kategoriach dla wybranych technologii węglowych

The analysis has shown the following order of technologies of power generation from coal according to their increasing impact on the environment:

- Fluidized-bed combustion (ACFB).
- Integrated gasification combined cycle with air gasification IGCC – air.
- Integrated gasification combined cycle with oxygen gasification IGCC – oxygen.
- Pulverized coal combustion with supercritical parameters.
- Oxy-combustion.

This order reflects the level of technology maturity with respect to their influence on environment.

5. OBJECTIVE FUNCTION AS A METHOD OF OPTIMIZATION IN PRIORITIZING TECHNOLOGIES OF COAL-BASED POWER GENERATION

Optimization of processes with several responses is carried out on the basis of one criterion with constraints in the form of equality or inequality. One of the most common ways of solving optimization process problem with multiple responses is adopting generalized choice function developed by Harrington. In order to obtain choice function *D*, measured values of responses are transformed into dimensionless choice scale *d*. It is individual subjective value of choice function. It is related to achieved results *y* with a following relation

$$d = \exp[-\exp(-y_1)] \tag{1}$$

where:

$y_1 = b_0 + b_1 y$,

y – result of the measurement,

b_0, b_1 – coefficients, which are determined for two values y determining appropriate values of choice function d (preferably $0.2 < d < 0.8$).

On the basis of responses transformed into scale *d*, with the use of arithmetic operation a given overall choice coefficient *D* can be achieved. Moreover, if one of the responses will be absolutely undesirable – overall choice function will be equal to 0, irrespectively of values of remaining results. Mathematical expression fulfilling this condition is arithmetic mean of individual choice functions:

$$D = (d_1 \cdot d_2 \cdot \ldots \cdot d_n)^{\frac{1}{n}} \tag{2}$$

where: n – number of measurements.

In this study, as y_i values, the following data being experts' assessment (in a scale 1–5) was adopted for an analysis:

y_1 – ensuring energy safety,

y_2 – possibility of implementing technology,

y_3 – technology efficiency,

y_4 – fixed costs,

y_5 – variable costs,

y_6 – technology failure frequency.

Results of experts' assessment for five selected technologies are presented in Fig. 3. As y_7 total value of ecoindicator was assumed, calculated by LCA and specified in Table 3. In this case minimum was searched when optimizing the function d_7.

For the described seven values of individual choice function, value of choice function *D* was found in accordance with the relation (2). The results have been shown in Fig. 3

Pulverized-coal combustion and fluidized bed combustion fulfil complex requirements better than gasification and oxy-combustion.

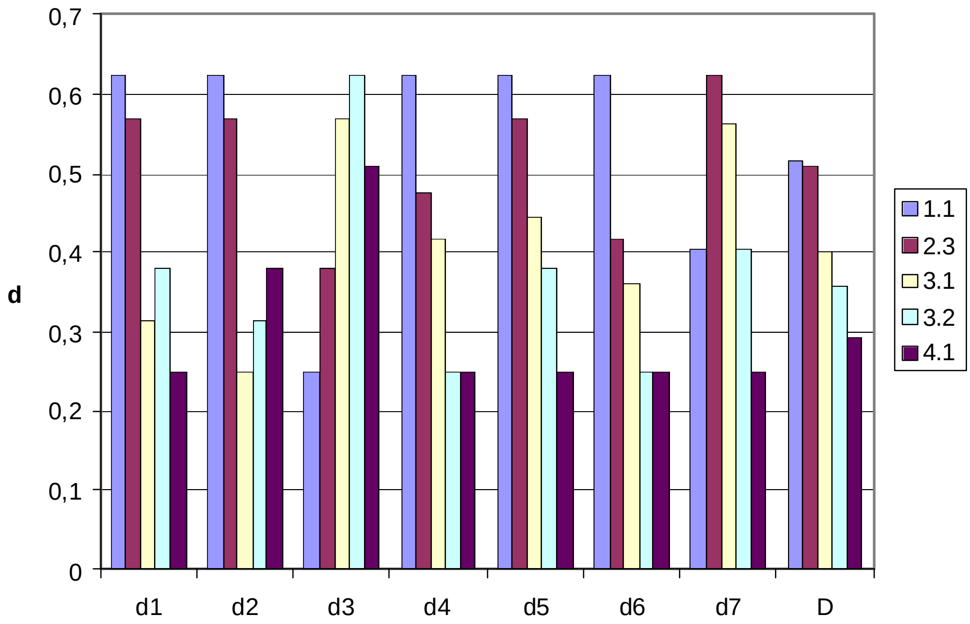

Fig. 3. Values of individual choice function d_i as well as value of overall choice function D for selected coal based power generation technologies

Rys. 3. Wartości szczegółowych funkcji wyboru d_i oraz wartość uogólnionej funkcji wyboru D dla wybranych analizowanych technologii energetycznego wykorzystania węgla

CONCLUSIONS

Taking into consideration the results of experts' assessment in the scope of energy safety and the possibility of implementation of technology – the five technologies under examination have been put in the following order: pulverized-coal combustion with supercritical steam parameters, atmospheric circulating fluidized-bed ACFB, integrated gasification combined cycle with oxygen gasification, oxy-combustion, integrated gasification combined cycle with air gasification.

In the second approach, taking additionally subsequent criteria, i.e. technology efficiency, fixed and variable costs as well as technology failure frequency (criteria designated as y_3, y_4, y_5, y_6) – the order is as follows: atmospheric circulating fluidized-bed ACFB, integrated gasification combined cycle with air gasification, integrated gasification combined cycle with oxygen gasification, oxy-combustion, pulverized-coal combustion with supercritical steam parameters.

The LCA results put the technologies in the following order: atmospheric circulating fluidized-bed (ACFB), integrated gasification combined cycle with air gasification, integrated gasification combined cycle with oxygen gasification = pulverized-coal combustion with supercritical steam parameters, oxy-combustion.

Final optimization with the use of D function gives the result:

- Pulverized-coal combustion with supercritical parameters = Atmospheric circulating fluidized-bed (ACFB).
- Integrated gasification combined cycle with air gasification.
- Integrated gasification combined cycles with oxygen gasification.
- Oxy-combustion.

The analysis carried out indicates that the most favourable results of assessment obtain technologies of high maturity level, whereas the poorest results seem to achieve technologies connected with oxygen utilization.

Combining the result of LCA with the results of experts' analysis caused slight but noticeable changes in technologies ranking. LCA take into account factors, which have considerable impact on natural environment (e.g. influence caused in building and demolition stages, influence caused by production of consumed material and environmental burdens connected with end of life stage). This is difficult to provide for in experts' analysis. Due to that fact involving LCA in technology prioritizing stage within foresight framework is entirely appropriate and allows to complete impartial results.

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Cover letter

Authors' intention was analysing possibilities of using results of technology assessment by LCA method in technological foresight projects. Analysis was based on selected processes from the field of coal-based power generation. In authors' opinion, results of experts' assessment, which is commonly used in foresight project, can be substantially enhanced and verified due to LCA.

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