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Clean Coal Technologies – a chance for Poland's energy security. Decision-making using AHP with Benefits, Opportunities, Costs and Risk Analysis

1. Introduction

The depletion process of the natural resources of hydrocarbon fuels, as well as the high prices of these energy carriers, simultaneously with the rapid increase in energy consumption and environmental restrictions, has resulted in a return to the wide use of coal not only as an energy carrier, but also as a raw material for the chemical industry. This fuel, in the entire process from production to combustion for energy use, creates numerous problems related to environmental protection requirements. Traditional methods of mining and burning coal are in conflict with the principles of sustainable development. The processes of mining and processing coal into energy or other raw materials for various industries are accompanied by the degradation of mining areas, the production of waste and industrial wastewater, and the emission of harmful gases into the atmosphere.

Security of energy supply combined with concern for the environment has become a powerhouse incentive for the adoption of CCT. Clean Coal Technologies aim at minimi-

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zing the negative environmental impacts of the industrial processing of coal. These impacts include large amounts of carbon dioxide, particulate matter, aromatic hydrocarbons, nitrogen and sulphur oxides emitted into the atmosphere. Such technologies include underground coal gasification and coal gasification technologies. The strategic objective of the development of coal gasification technology in Poland is to effectively substitute scarce hydrocarbon fuels and obtain the possibility of expanding the market for Polish coal. Production of synthetic natural gas (SNG) can open Polish coal mining to not only opportunities for further development, but also the potential to have a significant impact on the energy security of the entire European Union.

Eurostat data show that Poland, despite appearances, is one of the most independent countries in the European Union in terms of imports of energy and raw materials. We import only 30.7% of the strategic energy resources (mainly oil and gas) needed for the functioning of the economy. For comparison, Great Britain has a 42.2% energy dependence, France has 48.1%, and Germany imports as much as 61.1% of energy materials from abroad. *The Polish Energy Policy until 2030* is a document that was adopted by the Council of Ministers on 10 November 2009 in order to guarantee an adequate level for the country's energy security. This document still assumes the use of coal as the main fuel for power generation, as well as a primary fuel for heating (MG 2008, 2014). Since Poland's considerable coal resources can act as a stabilizer of energy security for the country, they are of particular importance to the Polish economy's dependence on gas (over 70%) and oil (95%) imports. The same document states that energy policy will be focused on diversifying the supply of raw materials and fuels, understood as not only the diversification of supply sources, but also the diversification of technology. The development of technologies for production of liquid and gaseous fuels from domestic raw materials will be supported. This creates the possibility for the development of coal gasification technology, which is seen as an attractive technology for the chemical sector. The flexibility of coal gasification technologies allows for, depending on the current demand for energy and raw material, the production of electricity, liquid fuels, hydrogen, methanol and substitute natural gas. Substitute natural gas may also be used as raw material for chemical syntheses.

Accordingly, this paper evaluated variants of coal gasification technologies for both energy use and chemical industry applications using a multi-criteria analytic hierarchy process (AHP) method in conjunction with an analysis of benefits, opportunities, costs and risks (BOCR analysis). In doing so, this paper has established strategic positions on the analysed technologies.

1. Background and Literature Review

In the literature concerning the assessment of energy and chemical technologies one can find numerous applications of the AHP method and BOCR analysis. In particular, Pilavachi and co-authors as well as Heo and others, used the AHP method to choose the optimal technology for hydrogen production, taking into account above-ground coal gasification technologies and selected factors in the area of opportunities, costs and risks (OCR) (Pilavachi et al. 2009; Heo et al. 2012). Lee and Mogi published an assessment of coal gasification as a hydrogen production technology in South Korea with the method of multi-criteria analysis (Lee et al. 2008). The basis of comparison presented in this study included, in particular, the expenditures on research and development of these technologies. The evaluation of energy security in China using the fuzzy sets method has also been provided by Ren and co-authors (Ren et al. 2014). These authors have identified and evaluated the strategic criteria describing the energy security of the country.

Saaty and co-authors (Saaty et al. 2001) used the AHP method for positioning the national needs of Sudan in terms of technology transfer where technologies like coal gasification and nuclear technology were assumed to be the least important goods. In turn, Golden and others used the AHP method to identify and evaluate the factors for forecasting acid rain (Acid Rain Policy) also taking into account the possible impact of coal gasification technology (Golden et al. 1989). Wang and others have used the AHP method to assess the technology of methanol and electric energy production in small and medium-scale poli-generation systems taking into account technical and economic factors directly related to this technology.

The use of the BOCR analysis in the evaluation of bioenergy technologies in Uganda can be found, among others, in the works of Okello and co-authors (Okello et al. 2014). As well, Noorollahi and co-authors conducted an evaluation and determined optimization strategies for energy technology development in Iran (Noorollahi et al. 2017). The themes of evaluation and development prospects for entire energy systems and technologies in the context of sustainable development using the multi-criteria AHP method and a BOCR analysis can be found in the papers by Scott and co-authors, as well as Wang et al. (Scott et al. 2012; Wang et al. 2009). These works used a BOCR analysis to look at the energy and chemical potentials of coal gasification technology, combustion under supercritical conditions and natural gas steam reforming in Poland. This was done in order to propose an appropriate development strategy for each technology. These technologies have been assessed on the same scale of energy consumption as the feed fuel (hard coal, lignite or natural gas) but the study has focused on the production of different final products (electricity, hydrogen, or methanol).

2. Coal Gasification Technologies

Coal gasification is a method of chemical processing, which consists of multidirectional thermal and chemical transformations taking place at elevated temperature. The transformation takes place predominantly between the organic part of the carbonaceous material and the gasifying factors, which may include: air, oxygen, carbon dioxide and steam, or a mixture thereof. Depending on the process conditions, products with different gas compositions are obtained. The most commonly used gasification of coal with oxygen and steam allows for the production of synthesis gas (CO and H_2), average heating value gas (about 16.7 MJ/m^3) or SNG (synthetic natural gas) with a calorific value of more than 33.5 MJ/m^3. The SNG is mainly methane. The possibility of obtaining gas of different compositions in a controlled manner owes to the gasification of coal currently being considered as a prospective method for chemical processing.

We may distinguish two main types of coal gasification (Stańczyk 2010; Minchener 2005): above-ground coal gasification and underground coal gasification. With above-ground coal gasification the process is carried out in specially designed reactors. Gasification reactor designs can be divided into three basic types depending on the structure of fuel flow in the reaction zone:

- *Moving bed reactors* are the most mature technology. There are only a few types of such reactors, most of which are based on Lurgi technology. The moving bed reactors can only be used for gasification of solid fuels such as coal, biomass or waste. They allow for the use of fuels with relatively high ash content (up to 35%).
- *Fluidized bed reactors* are currently the least used type of gas generator. Because of the low temperatures prevailing in the fluidized bed reactors (900–1050°C) they are most suitable for gasification of highly reactive coal types, i.e., lignite or lowly carbonized coals. Their advantage is the ability to work with different capacities. The sulphur contained in the fuel can be partially removed in the bed (up to 90%) through the use of sorbents, which allows for use of fuels with higher sulphur content, reduces corrosion and enables the use of cheaper materials in the construction of the reactors.
- *Entrained flow reactors* are currently the most widely used generators in gasification systems (in particular the Tech-1 and Tech-2). They are also the most versatile generators in that both solid and liquid fuel can be subjected to gasification. The gasification process in entrained flow reactors occurs at higher temperatures ranging from 1200 to 1600°C and at a pressure of 2 to 8 MPa.

In the case of above-ground coal gasification, fully mature commercial technologies are available and are being implemented on a wide scale. According to the 2015 report by The National Energy Technology Laboratory (NETL), a total of 862 coal gasification projects consisting of 2378 reactors, were in operation in the world. Of this number, 272 projects were commercially active (equipped with 686 reactors) with a total capacity of 116 GW_{th} (thermal power in the produced gas). At the same time, there were 82 plants currently under construction (262 reactors) with a capacity of 82.8 GW_{th} and a further 133 projects with 735 reactors in the planning phase (Table 1).

In the case of underground coal gasification (UCG), the gasification process involves the direct influence of the gasifying agents on coal deposits and the receipt of the resulting gaseous products on the surface (Palarski 1983; Palarski et al. 2009). The process is conducted in a georeactor or underground geological space, which is supplied with the necessary gasification agents through special drill holes (Figure 1). Usually air or oxygen, less often steam, are used as the gasifying agents. Gasification using air results in lean gas (3–4 MJ/m^3) with high nitrogen content (about 50–60% of volume), whereas gasification with oxygen, steam or their mixture, produces gas with a calorific value of 11–12 MJ/m^3. The obtained gas can be used to produce energy (preferably using *Integrated Gasification Combined Cycle*) for further chemical processing or for producing hydrogen.

Table 1. Gasification plants and reactors in the world in the years 1999 to 2015

Tabela 1. Instalacje i reaktory zgazowania na świecie w latach1999–2015

Year	Existing installations, gasification reactors and installations	Plants under construction, gasification reactors and installations	Installations planned, gasification reactors and installations	Existing installations, GWth	Plants under construction, GW_{th}	Installations planned, GW_{th}
1999	128/366	no data	33/48	42,7	no data	18,2
2001	131/409	no data	32/59	43,3	no data	24,5
2004	117/385	no data	38/66	43,0	no data	25,3
2007	144/427	no data	10/34	56,2	no data	36,5
2010	192/405	11/17	37/76	70,8	10,9	40,4
2013	234/618	61/202	98/550	104,7	63,4	84,0
2015	**272/686**	**82/262**	**133/735**	**116,6**	**82,8**	**109,2**

Source: The National Energy Technology Laboratory (NETL).

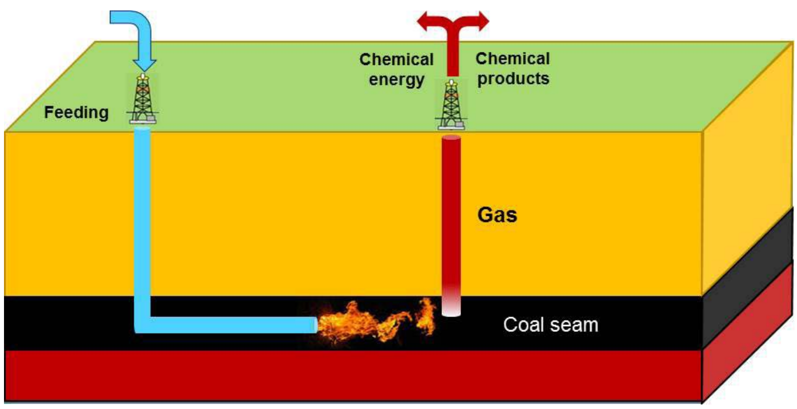

Fig. 1. Underground coal gasification using directional drill holes
Source: own study

Rys. 1. Metoda podziemnego zgazowania węgla z wykorzystaniem otworów kierowanych

There are two distinct methods for preparing the georeactor: shaft and no-shaft. The two methods differ from each other mainly in the method of accessing the coal deposit. The first method includes driving roadways in the seam or using existing networks of roadways connected to the system of surface generators supplying the gasification agents. The products are received through shafts or vertical drill holes. This method is considered unprofitable due to the associated high costs, though it may be used in liquidated mines. The second method, which is based on accessing the coal seam, uses a directional drilling method derived from the oil and gas industry. This method currently dominates. In the case of underground coal gasification, the technology involved is still in the early stages of development.

3. Evaluation of the Selected Energy and Chemical Technologies

3.1. The choice of coal gasification technology

The selection of coal gasification technologies included mainly variants of above-ground coal gasification. It was possible with these technologies, to assess the associated costs and risks. As well, these technologies were considered to be ready for implementation on a commercial scale. Variants of underground coal gasification were also analysed.

The analysed variants were a combination of the following:

- Different final products (electricity produced in combination with heat and/or hydrogen and methanol).
- The availability of certain types of coal (hard coal, lignite).
- Availability for the geological sequestration of carbon dioxide (carbon capture and storage, CCS), or the absence thereof.
- Type of technology: Tech-1, Tech-2, steam methane reforming (SMR) or supercritical pulverized coal combustion (SPC).

The set of analysed variants of technology included:

- Eight variants of technology aimed at electricity generation from hard coal and lignite, with and without CCS (four variants of Tech-1 technology and four variants of the SPC technology).
- Eight variants of technology aimed at the production of hydrogen from hard coal and lignite, with and without the CCS technology, using Tech-1, Tech-2, and steam reforming of natural gas technologies.
- Six variants focused on production of methanol (variants with Tech-1 and steam methane reforming (SMR) technologies).
- Four variants of underground coal gasification focused on the generation of electricity from hard coal, with and without the CCS for both shaft and no-shaft methods.

The basis for the strategic evaluation of the proposed technologies for coal gasification included factors related to energy security. These factors included, legal and formal factors (emission standards and related costs), social factors and the ability to achieve better economic efficiency alongside increasing environmental requirements (Kwaśniewski and Kopacz 2015).

3.2. Technology assessment methodology

In the evaluation of positive and negative impacts and the selection of alternative energy and chemical technologies, a methodology was developed using the AHP method while taking into account the BOCR analysis. The BOCR analysis is an analysis of the benefits (B), opportunities (O), costs (C) and risks (R) of the technology in question (Saaty 2001, 2004; Saaty and Ozdemir 2004; Diederik and Wijnmalen 2005; Sobczyk et al. 2011; Trzaskalik 2008). The developed procedure consisted of four sequential stages (Figure 2).

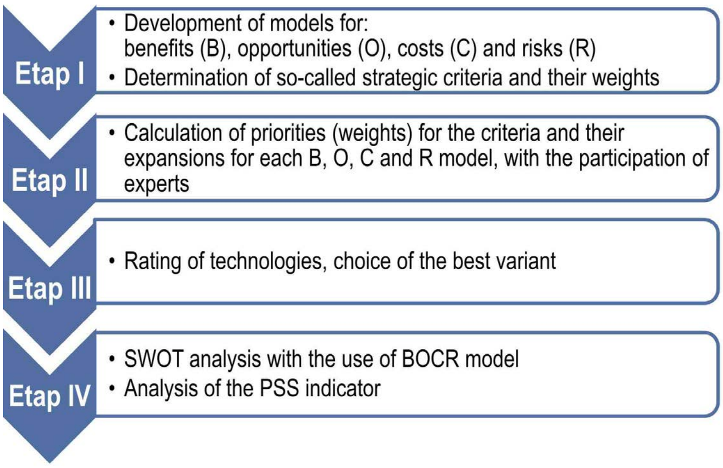

Fig. 2. Stages of the coal gasification analysis with the use of AHP
Source: own study

Rys. 2. Etapy analizy zgazowania węgla z wykorzystaniem AHP

3.2.1. Valuation of the strategic criteria and their weights

To determine the degree of significance of each BOCR model in choosing the optimal technology, strategic criteria deemed important by experts have been used. The strategic criteria, according to the procedure, were designed in such a way that the problem of choosing the best technology for coal gasification can be described with a broader perspective. The strategic criteria were evaluated in their significance related to the assessment of the conditions around the analysed technological variants. As a result, the following strategic criteria were selected:

- Economic (E),
- Technological (T),
- Environmental (S),
- Legal and formal (R).

Figure 3 shows a model that helped in the expert evaluation of the strategic criteria.

The weights for the strategic criteria were obtained in accordance with the AHP methodology. Experts compared pairs of criteria dependent on the strategic objective; selection of the best coal gasification technology. Vectors of weights with the components, $W = [0{,}31_E; 0{,}11_T; 0{,}05_Ś; 0{,}53_R]$, were obtained.

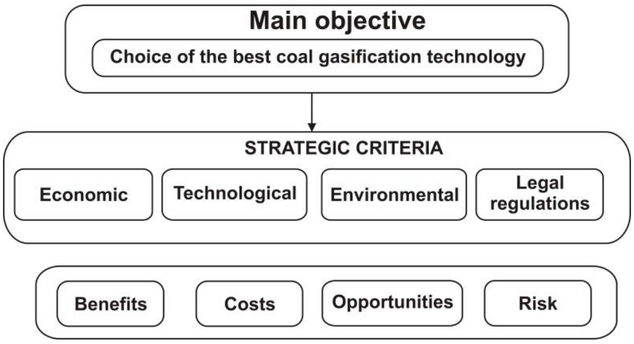

Fig. 3. Hierarchical model of the strategic criteria to assess the validity of the benefits, costs, opportunities and risks
Source: own study

Rys. 3. Model hierarchiczny kryteriów strategicznych do oceny ważności korzyści, kosztów, szans i ryzyka

Table 2. Scale for evaluation of b, o, c, r weights

Tabela 2. Skala do oceny wag b, o, c, r

Verbal description	Weight
Very big	0.42
Big	0.26
Average	0.16
Small	0.10
Very small	0.06

Source: own study.

Subsequently, the experts evaluated each of the strategic criteria given their benefits, opportunities, costs and risks. One of the verbal scales developed by Saaty was adopted to quantify the impact and is presented in Table 2 (Saaty 1997).

The results of the respective intensities assigned to each of the strategic criteria are summarized in Table 3.

Table 3. The results of the experts' estimates of the significance of B, O, C and R

Tabela 3. Wyniki eksperckiego oszacowanie istotności B, O, C i R

Strategic criteria	Benefits	Costs	Opportunities	Risk
Economic (0.31)	big (0.26)	very big (0.42)	big (0.26)	very big (0.42)
Technological (0.11)	average (0.16)	big (0.26)	big (0.26)	big (0.26)
Environmental (0.05)	big (0.26)	big (0.26)	average (0.16)	big 0.26
Legal and formal regulations (0.53)	big (0.26)	big (0.26)	big (0.26)	big (0.26)
The resulting weight	0.22	0.27	0.23	0.27

Source: own study.

Experts estimated four models for determining the impact of various strategic criteria on the choice of the best technology. From the estimated intensities and weights calculated for strategic criteria, the final BOCR weights were calculated. The results of the calculations show that the highest weights were obtained for the risk model (0.27) and the cost model (0.27), followed by opportunities (0.23) and benefits (0.22). The resulting BOCR weights were included in the calculations of individual B, O, C and R models.

3.2.2. Characteristics of particular models

Benefits model – B

The most important benefits associated with the selection of a specific variant of coal gasification technology are divided into three groups of criteria:

- B1 – Economic.
- B2 – Technical.
- B3 – Environmental.

The particular technical benefits refer to:

- B2.1 – The degree of efficiency of the conversion of raw materials to product [%].
- B2.2 – Own consumption of energy [MW].

- B2.3 – Availability (operating time) [%].
- B2.4 – The possibility of using non-standard fuels.

Environmental criteria are connected with:

- B3.1 – The purchase of CO_2 emission rights [USD].
- B3.2 – The need for processing water [m^3/min].

One of the important advantages from the economic point of view are the revenues generated by a given coal gasification technology (B1.1). Using the established individual benefits, a model for Benefits analysis was developed (Figure 4).

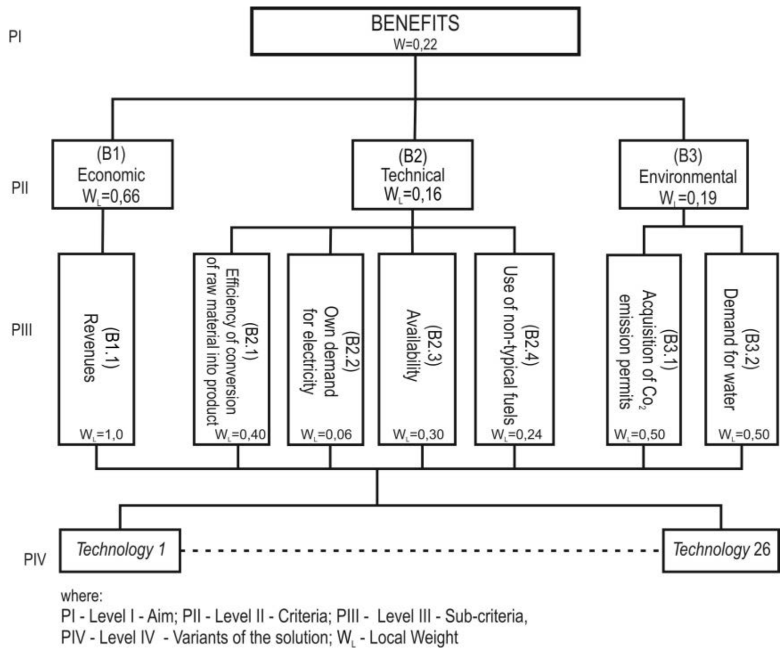

Fig. 4. Hierarchical model of benefits
Source: own study

Rys. 4. Model hierarchiczny korzyści (Benefits)

Opportunities model – O

The analysis of opportunities involved the examination of those circumstances, which with skilful use, will have a positive influence on the development of the technological options under consideration. Four groups of criteria were distinguished:

- O1 – Market factors related to diversification of the resource base (O1.1).
- O2 – Social factors, which will in particular, influence the creation of jobs (number of employees), and thus economic activity in the region (O2.1).
- O3 – Environmental factors in which one can observe the reduction of CO_2 emissions [CO_2 emissions into the atmosphere – Mg/h] (O3.1).

A hierarchical model of the analysis of opportunities is presented in Figure 5. Similar to the Benefits model, appropriate calculations in accordance with the AHP methodology were conducted in order to obtain final weights for the options analysed in terms of opportunities.

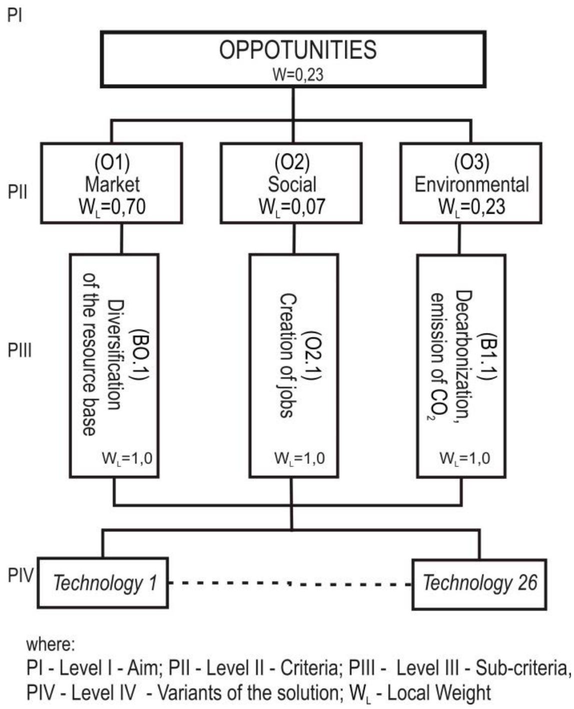

Fig. 5. Hierarchical model of opportunities
Source: own study

Rys. 5. Model hierarchiczny szans (Opportunities)

Costs model – C

Alongside the described advantages, specific costs are related to the selection and implementation of any particular technological variant. Four groups of cost criteria were distinguished:

C1 – The current value NPVR of return on investment taking risk into account, [%].

C2 – Fuel feed costs [USD].

C3 – The operating costs (including labour costs, maintenance, etc.) [USD].

C4 – The environmental costs (cost of water, waste disposal, sewage) [USD].

The structure of the cost analysis model is shown in Figure 6.

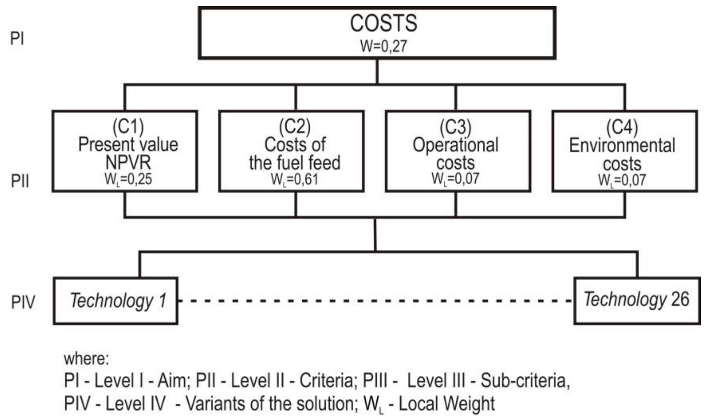

Fig. 6. Hierarchical model of costs
Source: own study

Rys. 6. Model hierarchiczny koszty (Costs)

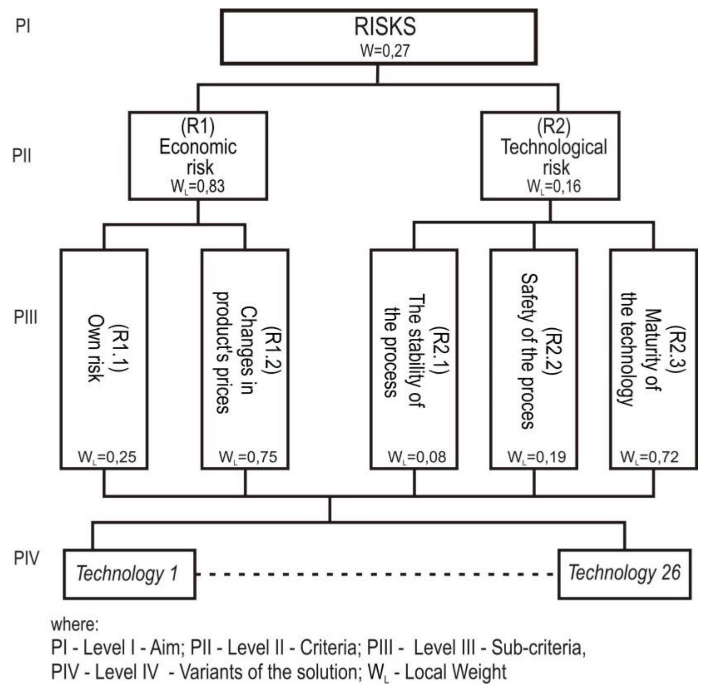

Fig. 7. Hierarchical model for risk
Source: own study

Rys. 7. Model hierarchiczny ryzyka (Risks)

Risks model – R

The last model in the BOCR analysis was developed for risk. The risk associated with coal gasification technology was divided into two areas:

- R1 – Economic.
- R2 – Technological.

Economic risk in particular is related to:

- R1.1 – Technology investment risk [indicator – %].
- R1.2 – Risks associated with changes in price of the product [indicator – %].

The risks associated with technological considerations take into account the following factors:

- R2.1 – Stability of the process [indicator].
- R2.2 – Safety of the process [indicator].
- R2.3 – Maturity of the technology [indicator – %].

The structure of the risks analysis model is shown in Figure 7.

4. Ranking of the Coal Gasification Technology Using BOCR Analysis

The final assessment of the variants from the perspectives of *Benefits, Opportunities, Costs and Risks* is summarized in Table 4. The conducted evaluation allowed for the ranking of options and the identification of the best variants of coal gasification technology. This was done in accordance with the *Additive-negative formula:* $b{\cdot}B+o{\cdot}O-c{\cdot}C-r{\cdot}R$.

Analysing the summarized results, one can notice that the highest score in the presented ranking was acquired by the following technologies:

- **Tech-1_B_MeOH_1 (6,48)** – Gasification of lignite to methanol using Tech-1 reactor entrained flow, with CCS system,
- **Tech-1_K_MeOH_1 (6,41)** – Gasification of hard coal to methanol using Tech-1 reactor entrained flow, with CCS system,
- **Tech-1_K_MeOH_0 (6,19)** – Gasification of hard coal to methanol using Tech-1 reactor entrained flow, without CCS system,
- **Tech-1_B_MeOH_0 (6,15)** – Gasification of lignite to methanol using Tech-1 reactor entrained flow, without CCS system.

Analysing the final results according to the partial ratings of the four B, O, C, and R models, one can observe that the highest rated technologies, also in terms of the partial results, are characterized by high values for positive factors (opportunities and benefits) and low values for negative factors (risks and costs).

Table 4. The final ranking of the evaluated variants (coal gasification technologies)

Tabela 4. Wynikowy ranking ocenianych wariantów decyzyjnych (technologii zgazowania węgla)

No.	Rating of the technology	BOCR indicator	PSS	No.	Rating of the technology	BOCR indicator	PSS
1.	Tech-1_B_MeOH_1	6.48	0.73	14.	PZW-A_E_0	–2.43	0.37
2.	Tech-1_K_MeOH_1	6.41	0.73	15.	Tech-1_K_H2_0	–2.45	0.40
3.	Tech-1_K_MeOH_0	6.19	0.78	16.	PZW-A_E_1	–2.5	0.35
4.	Tech-1_B_MeOH_0	6.15	0.78	17.	PC_K_E_1	–2.5	0.35
5.	Ref_G_MeOH_0	5.22	0.75	18.	PZW-B_E_0	–2.55	0.35
6.	Ref_G_MeOH_1	4.32	0.68	19.	Tech-1_B_H2_0	–2.55	0.39
7.	Tech-1_K_H2_1	–1.53	0.45	20.	Tech-2_K_H2_0	–2.8	0.38
8.	Tech-1_B_H2_1	–1.65	0.44	21.	PZW-B_E_1	–2.84	0.33
9.	Tech-2_K_H2_1	–2.03	0.42	22.	Tech-1_B_E_0	–2.89	0.30
10.	Tech-1_B_E_1	–2.15	0.37	23.	Ref_G_H2_1	–2.9	0.41
11.	PC_B_E_1	–2.23	0.36	24.	Tech-1_K_E_0	–3.04	0.30
12.	Tech-1_K_E_1	–2.35	0.36	25.	PC_B_E_0	–3.23	0.26
13.	Ref_G_H2_0	–2.39	0.42	26.	PC_K_E_0	–3.23	0.28

Source: own study.

Symbols for coal gasification technologies:

- Types of above-ground coal gasification technologies:
  - Tech-1, Tech-2.
  - Ref – steam methane reforming (SMR).
  - PC – supercritical pulverized coal combustion (SPC).
  - PZW – underground coal gasification (UCG); A-no-shaft method, B-shaft method.
- Coal type:
  - K – hard coal.
  - B – lignite.
- Final product:
  - MeOH – methanol.
  - H2 – hydrogen.
  - E – electricity.
- CO2 sequestration module:
  - 0 – without CCS system.
  - 1 – with CCS system.

5. SWOT Analysis Using a BOCR Model

The B, O, C and R models which were used to rank alternative coal gasification technologies, were later used in the SWOT analysis, which provides a good basis for determining the strategic position and identifying the types of development strategies for the object of this evaluation. The SWOT factors correspond with the quantified (weighed) factors of the BOCR analysis, where:

- S (strengths) = B (benefits).
- W (weaknesses) = C (costs).
- O (opportunities) = O (opportunities).
- T (threats) = R (risk).

Strengths and weaknesses are examined in relation to internal factors, while opportunities and threats are examined in relation to external factors. By analogy, similarity to the BOCR analysis is obtained (Saaty 2008).

Point mapping of the strategic positions, P(x, y), of the evaluated technological variants were determined. Point mapping helped determine the quadrant in which the evaluated technology was located. The individual quadrants of the system correspond to one of the four basic strategic positions: WO – competitive strategy, SO – aggressive strategy, WT – defensive strategy and ST – conservative strategy. In the SWOT method, choice of strategy depends on the strength of the links between groups of factors. There are 4 normative strategies (Table 5).

The dynamic (aggressive) strategy (MAXI-MAXI) applies to a situation in which the strengths dominate internally, while the external environment is dominated by opportunities. The strategy addresses strong expansion and diversified development. It involves the best use of the opportunities arising from the favourable internal and external conditions.

Table 5. Matrix of normative strategies

Tabela 5. Macierz normatywnych strategii działania

Specification		External factors	
		Opportunities	Threats
Internal factors	Strengths	Dynamic (aggressive) strategy (SO) MAXI-MAXI	Conservative strategy (ST) MAXI-MINI
	Weaknesses	Competitive strategy (WO) MINI-MAXI	Defensive strategy (WT) MINI-MINI

Source: own study based on (Weihrich 1982).

Competitive strategy (MINI-MAXI) is distinguished by the dominance of weaknesses over strengths under favourable external conditions. This strategy should rely on the use of opportunities while simultaneously reducing or correcting internal shortcomings (weaknesses).

Conservative strategy (MAXI-MINI) uses the advantage of strengths over weaknesses, within adverse external conditions. The conducted activities should be aimed at reducing the impact of threats and at the more effective use of opportunities.

Defensive strategy (MINI-MINI) is associated with a situation in which weaknesses and associated risks are dominant. There are no decisive strengths to oppose the existing threats. This strategy is intended to ensure survival of the object of analysis by taking action against negative circumstances.

The probability of strategic success (PSS) was also calculated. PSS refers to "the chance of success" of the analysed coal gasification technology. The PSS indicator is given by:

$$PSS = \frac{AR+PR}{2} \tag{1}$$

Where PR indicates the technology's market position or is see as the "indicator of the potential of strong internal characteristics".

$$PR = \frac{\Sigma(S)}{\Sigma(S+W)} \tag{2}$$

AR refers to the technology's market attractiveness or the, "index of attractiveness of the technology in the environment".

$$AR = \frac{\Sigma(O)}{\Sigma(O+T)} \tag{3}$$

A value of PSS above 0.5 is assumed to be a condition for success, or at least of good functioning of technology. Values below this indicate that the technology has no chance of development and investment is subject to considerable risk. As a result of the conducted calculations, point mapping was obtained for the assessed technological variants of coal gasification (Figure 8).

Analysing the location of the various assessed coal gasification technologies, it can be noted that the coordinates of internal and external conditions rarely exceed, in absolute value, the value of 0.1. This may mean that the strategies are still poorly developed and are of mixed character. The tendency for the development of an aggressive growth strategy, which is based on the advantage of strengths and opportunities, is demonstrated by four coal gasification technologies: Tech-1_K_MeOH_0, Tech-1_B_MeOH_0, Tech-1_K_MeOH_1 and Tech-1_B_MeOH_1. The outlined strategic direction seems to be relatively well developed.

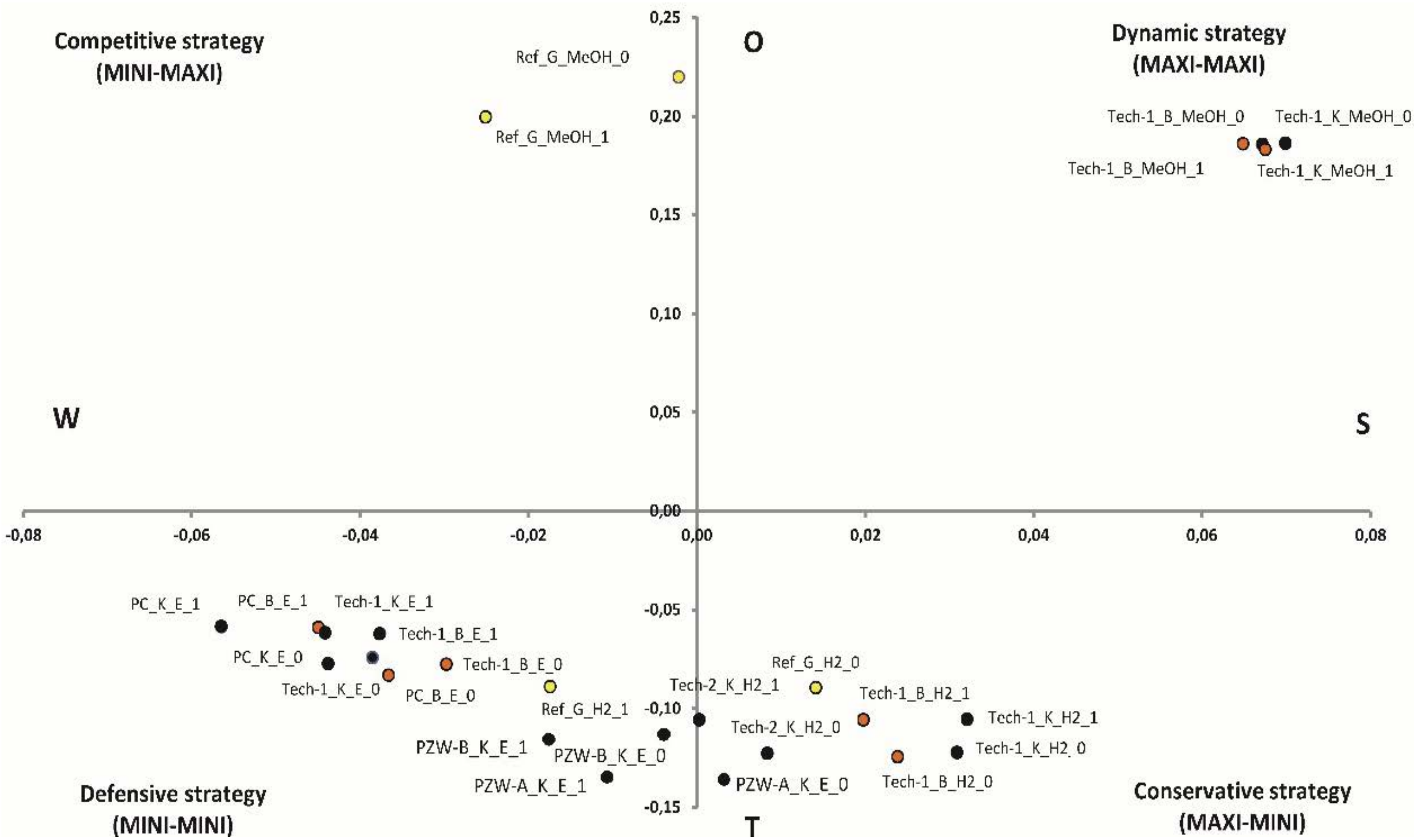

Fig. 8: Strategic position of the analysed gasification technology on the basis of SWOT analysis

Rys. 8. Pozycja strategiczna analizowanych technologii zgazowania na podstawie analizy SWOT

In contrast, the values of the probability of strategic success (PSS) for these technologies are as follows: 0.780, 0.781, 0.731 and 0.733 (Table 4). The PSS values are significantly above 0.5. This means that these technologies are prospective and have a chance for development.

The Tech-1_K_MeOH_0 technology shows strengths related to economic factors and a low rate for the technology's own demand for energy. This technology also has a high degree of efficiency in the conversion of raw materials to products. A benefit of this technology's implementation is also the diversification of the resource base, and thus, the substitution of imported natural gas.

Factors for the development of the Tech-1_K_MeOH_1 technology also include economic benefits. Strengths of the assessed technology revealed themselves in terms of the environmental benefits associated with low levels of CO_2 emissions and the reduced need to purchase CO_2 emissions allowances. The technology is also characterized by a high diversification of the resource base and good prospects for reducing CO_2 emissions (CCS system).

For the technologies Ref_G_MeOH_0 and Ref_G_MeOH_1 a mixed strategy is outlined with a weaker indication of a competitive strategy. The analysed strategies are characterized by a PSS indicator above 0.5, scoring 0.747 and 0.684 respectively. This shows opportunities for growth.

The other analysed above-ground coal gasification technologies indicate mixed strategies leaning towards the defensive or conservative quadrants. Conservative strategies are characterized by a good system of internal factors and are distinguished by a relatively high investment risk. In turn, the technologies indicating a defensive strategy are characterized by unfavourable internal factors and are subject to considerable risk. The PSS indicator of these technologies is below 0.5, which confirms these situations.

In the case of underground coal gasification, all variants indicate a defensive strategy. PSS ratio is below 0.5, which means that this technology is not yet ready for implementation on a commercial scale and investment is subject to very high risk.

Conclusions and Policy Implications

The comprehensive use of available domestic energy resources, mainly hard coal and lignite due to their large resource base, is the basis for the development of Poland's economy and energy security. In light of Polish obligations resulting from the requirements of European Union directives, the implementation of advanced low carbon technologies is a necessary condition for maintaining coal's leading position in Poland. The so-called clean coal technologies include: high-efficiency low-emission coal-fired energy units, oxidative combustion of coal in pulverized and fluidized beds and the gasification of coal for energy and chemical purposes. All of these technologies can be integrated with CO_2 capture and sequestration.

Coal gasification is seen as a potentially attractive technology for the Polish economy both for the chemical sector and the mining sector. In the chemical sector coal gasification creates opportunities for the diversification of the resource base thus reducing the influence of crude oil and natural gas suppliers. In the mining sector, coal gasification allows for the expansion of products beyond the energy and metallurgical industries, market expansion and the ability to increase (maintain) the level of production in the long term. Working on the commercial implementation of coal gasification technologies will ensure the effective substitution of scarce hydrocarbon fuels. However, it will be a challenge to Polish industrial policy for clean coal technologies.

Analysis of coal gasification technology using BOCR and SWOT analyses as decision support procedures helped determine the ranking of technologies and the types of development strategies for the analysed technological variants. The highest-ranking technologies included those aimed at the production of methanol with the geological sequestration of carbon dioxide (CCS): Tech-1_B_MeOH_1 and Tech-1_K_MeOH_1. The variants Tech-1_K_MeOH_0 and Tech-1_B_MeOH_0 were also highly ranked. The production of methanol is the most attractive area of application given the scale of production and the further processing of olefins (ethylene and propylene), as well as the future possibility for the direct substitution of liquid and gaseous fuels produced from methanol. These technologies were found to be in coordination with an aggressive growth strategy, which is based on the superiority of strengths and opportunities. The developed indicators have shown that these are promising technologies, which have a chance for further growth.

The group of technologies focused on the production of hydrogen (Tech-1_K_H2_1, Tech-1_B_H2_1 and Tech-2_K_H2_1) were also high up in the ranking. Due to the current scale of application, production of hydrogen and ammonia is seen to be an attractive segment of the fuel market that provides the highest level of substitution with natural gas. This is important for Polish energy security. Other analysed coal gasification technologies indicated mixed strategies of defensive and conservative positions.

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CZYSTE TECHNOLOGIE WĘGLOWE SZANSĄ BEZPIECZEŃSTWA ENERGETYCZNEGO POLSKI. WSPOMAGANIE DECYZJI WYBORU Z WYKORZYSTANIEM METODY AHP, W POWIĄZANIU Z ANALIZĄ KORZYŚCI, MOŻLIWOŚCI, KOSZTÓW ORAZ RYZYKA

Słowa kluczowe

czyste technologie węglowe, zgazowanie węgla, bezpieczeństwo energetyczne, wybór wariantów decyzyjnych, Hierarchiczna Analiza Problemu AHP z analizą BOCR

Streszczenie

Perspektywa wyczerpywania się naturalnych zasobów paliw węglowodorowych, jak też wysokie ceny tych nośników z jednej strony, z drugiej zaś gwałtowny wzrost zużycia energii i ograniczenia ekologiczne, spowodowały powrót do koncepcji szerokiego wykorzystania węgla nie tylko jako nośnika energii, ale również jako surowca dla przemysłu chemicznego. Paliwo to jednak, w całym procesie od wydobycia, poprzez spalanie, do wykorzystania zawartej w nim energii, stwarza liczne problemy związane z wymogami ochrony środowiska. Tradycyjne metody wydobycia i spalania węgla stoją w sprzeczności z zasadami polityki zrównoważonego rozwoju. Procesom wydobywczym i przetwórczym węgla w energię lub inny surowiec dla różnych gałęzi przemysłu, towarzyszy degradacja terenów górniczych, produkcja odpadów i zanieczyszczonych wód oraz emisja szkodliwych gazów do atmosfery.

Zabezpieczenie dostaw energii połączone z troską o ochronę środowiska stało się motorem napędowym programów dla technologii czystego węgla. Czyste technologie węglowe (CTW) mają na celu minimalizację negatywnego wpływu procesu przemysłowego przetwarzania węgla na środowisko, takich jak emitowanych do atmosfery znacznych ilości ditlenku węgla, cząstek stałych, tlenków azotu i siarki. Takimi technologiami są m.in. podziemne i naziemne zgazowanie węgla.

Technologia zgazowania pozwala na wielokierunkowe wykorzystanie węgla od produkcji energii elektrycznej i ciepła po produkcję substancji chemicznych, w tym paliw płynnych i gazowych.

Strategicznym celem rozwoju technologii zgazowania węgla w Polsce jest podjęcie efektywnej substytucji deficytowych surowców węglowodorowych oraz uzyskanie możliwości poszerzenia rynku dla polskiego węgla. Produkcja substytutu gazu ziemnego (SNG) może otworzyć przed polskim górnictwem węglowym nie tylko szanse dalszego rozwoju, ale również w istotny sposób wpłynąć na bezpieczeństwo energetyczne całej Unii Europejskiej.

W artykule przedstawiono analizę technologii zgazowania węgla przy zastosowaniu procedur wspomagania decyzji, analiz BOCR i SWOT. Procedury te pomogły określić ranking technologii i typów strategii rozwojowych, które są prawdopodobne dla analizowanych odmian technologicznych. Biorąc pod uwagę warunki polskiej gospodarki, najwyższy ranking uzyskały technologie naziemnego zgazowania ukierunkowane na wytwarzanie metanolu z modułem sekwestracji geologicznej ditlenku węgla (CCS). W przypadku podziemnego zgazowania węgla stwierdzono, że technologia nie jest jeszcze gotowa do wdrożenia na skalę komercyjną, a inwestycja obarczona jest bardzo wysokim ryzykiem.

CLEAN COAL TECHNOLOGIES – A CHANCE FOR POLAND'S ENERGY SECURITY. DECISION-MAKING USING AHP WITH BENEFITS, OPPORTUNITIES, COSTS AND RISK ANALYSIS

Keywords

clean coal technologies, coal gasification, energy security, choice of decision variants, Analytic Hierarchy Process with BOCR

Abstract

The comprehensive use of available domestic energy resources, mainly coal and lignite, is the basis for the development of Poland's economy and energy security due to the country's large resource base. The implementation of clean coal technologies (CCT) is a necessary condition for maintaining coal's leading position in Poland. Coal gasification technologies are seen as potentially attractive for the Polish economy, both for the chemical sector as well as for the mining sector. Working on the commercial implementation of coal gasification technologies, which ensures the effective substitution of scarce hydrocarbon fuels, will be a challenge to Polish industrial policy and support for CCT. This paper presents an analysis of coal gasification technologies using the decision support procedures, BOCR and SWOT analyses. These procedures helped determine the ranking of technologies and the types of development strategies plausible for the analysed technological variants. Taking into consideration the conditions of the Polish economy, the highest-ranking technologies included those aimed towards the production of methanol with the geological sequestration of carbon dioxide (CCS). In the case of underground coal gasification, it was found that the technology is not yet ready for implementation on a commercial scale and investment is subject to very high risk.