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Том 69

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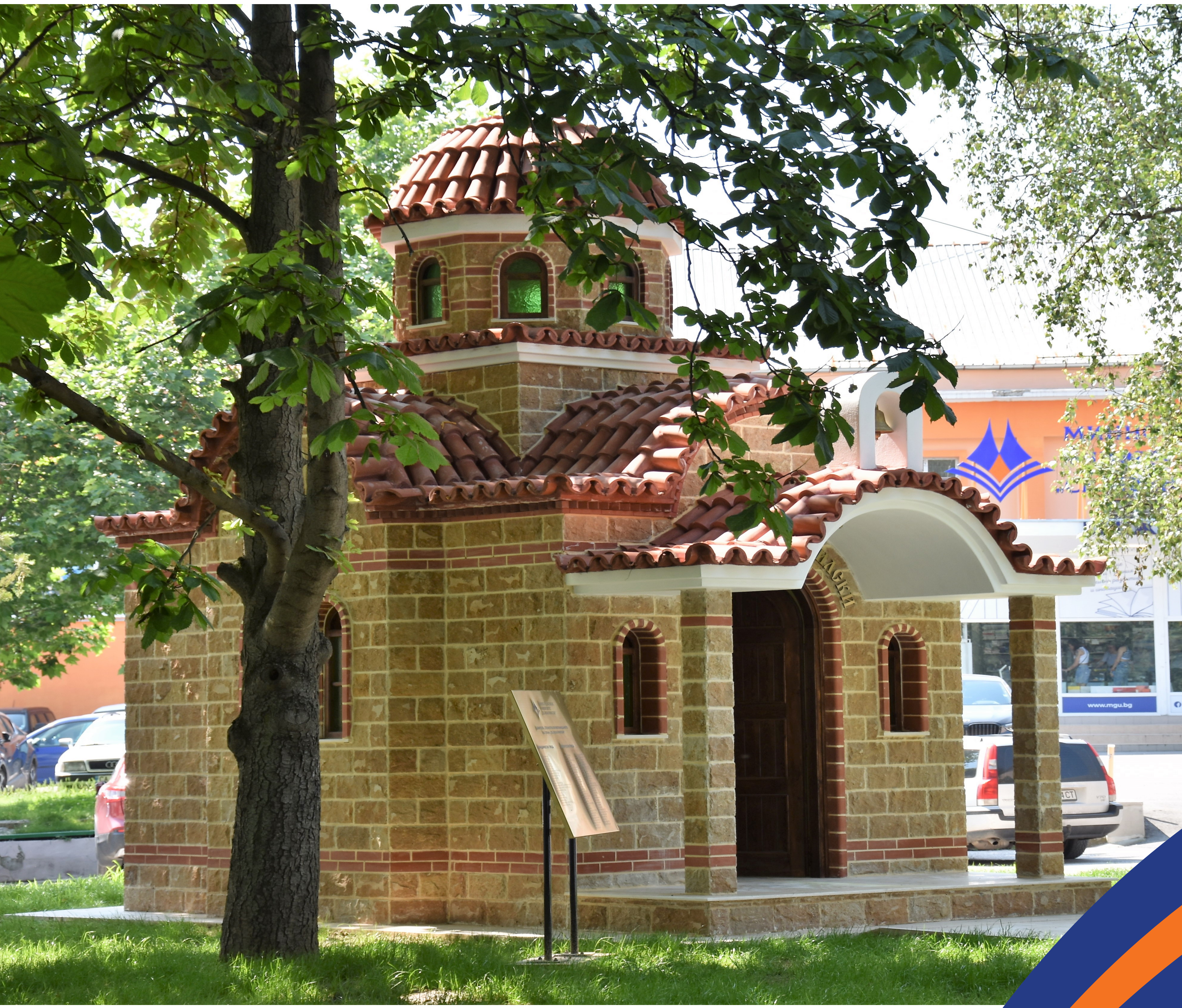

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MULTI-CRITERIA ASSESSMENT OF THE SUITABILITY OF COAL DEPOSITS IN THE PELAGONIAN BASIN FOR UNDERGROUND COAL GASIFICATION

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ABSTRACT. Underground coal gasification (UCG) represents a modern technology for the utilisation of coal resources that are difficult to access or economically unfeasible for conventional mining. This paper presents a multi-criteria assessment of the suitability of coal deposits in the Pelagonian Basin for the application of underground coal gasification. The selection of a coal deposits suitable for UCG depends on a number of parameters related to coal properties, seam characteristics, hydrogeological conditions, and surface infrastructure. The most important factors include coal rank, seam thickness and depth, the type of overburden and underlying strata, permeability and porosity of the coal and surrounding rocks, geological characteristics, such as structural and tectonic features, groundwater level and its chemical composition, as well as proximity to surface infrastructure. For an integrated evaluation, a multi-criteria model was applied, enabling the ranking of coal deposits according to their suitability for the gasification process. The result indicates variable suitability of the analysed deposits, with certain zones standing out as having higher potential for the successful application of this technology.

Key words: underground coal gasification (UCG), Pelagonian Basin, coal, ecology, multi-criteria assessment.

МНОГОКРИТЕРИАЛНА ОЦЕНКА НА ПРИГОДНОСТТА НА ВЪГЛИЩНИТЕ НАХОДИЩА В ПЕЛАГОНИЙСКИЯ БАСЕЙН ЗА ПОДЗЕМНА ГАЗИФИКАЦИЯ НА ВЪГЛИЩА

Радмила Каранакова Стефановска, Зоран Панов, Ристо Поповски, Благица Донева

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РЕЗЮМЕ. Подземната газификация на въглища представлява съвременна технология за използване на въглищни ресурси, които са труднодостъпни или икономически неизгодни за конвенционален добив. В настоящата работа е представена многокритериална оценка на пригодността на въглищните находища в Пелагонийския басейн за прилагане на подземна газификация на въглища. Изборът на подходящо въглищно находище за подземна газификация на въглища зависи от редица параметри, свързани със свойствата на въглищата, характеристиките на пласта, хидрогеоложките условия и повърхностната инфраструктура. Най-важните фактори включват ранг на въглищата, дебелина и дълбочина на пласта, тип на покривните и отдолу лежащите скали, пропускливост и порестост на въглищата и околните скали, геоложки характеристики, като напр. структурни и тектонични особености, ниво на подземните води и техния химичен състав, както и близост до повърхностна инфраструктура. За цялостна оценка е приложен многокритериален модел, който позволява аранжиране на въглищните находища според тяхната пригодност за процеса на газификация. Резултатите показват променлива пригодност на анализираните находища, като определени зони се открояват с по-висок потенциал за успешно прилагане на тази технология.

Ключови думи: подземна газификация на въглища, Пелагонийски басейн, въглища, екология, многокритериална оценка.

1. Introduction

The energy situation in the world and the international marker for energy resources have drawn attention to the need for intensive and efficient implementation of the plan for ensuring a more secure energy future.

With the increasing need for energy, both in quantitative and qualitative terms, the need for the natural energy raw material base to be used in a techno-economic and ecologically optimal manners is becoming more pronounced.

Coal is still an important energy source in many countries; however, classical methods of exploitation are associated with significant economic, technical, and environmental challenges, especially when it comes to deep, thin or complex geological coal seams. In this context, underground coal gasification (UCG) is emerging as an innovative technology that enables the utilisation of coal resources *in situ*, without the need for traditional conventional exploitation methods. This should be especially relevant in our country, which does not have sufficient and structurally favorable reserves of energy raw materials. Coal deposits in this country represent the most important coal deposits in the region, with significant reserves and diverse geological conditions. The deposits from Pliocene complex taken as representative deposits are: the *Mariovo* deposit from the Mariovo basin and deposits in the Pelagon basin PJS in the *Suvodo* and *Živojno* open pits.

However, not all parts of the deposit are equally suitable for the application of underground gasification, which imposes the need for a systematic and scientifically based assessment of their suitability. Previous research conducted in the field of underground coal gasification has shown that a large number of pilot projects and tests have been conducted on almost all types of coal (from lignite to anthracite), at different depths, in layers with different lithologies, and under a variety of geological and hydrogeological conditions (Ghose, 2007). The success ranged from completely unsatadfactory to completely acceptable.

2. Determination of criterion functions for selecting a suitable site for underground gasification

Criteria that were highlighted when developing the model for the applicability of UCG are:

1) Type of coal: lower quality coal types, especially lignite and subbituminous types are recommended for UCG (Bialecka, 2009);
2) Seam thickness: research has shown that the ideal thickness of the coal seam is 5-10 m, with a minimum of 2 m. (Shafirovich, 2009)-(Thompson, 1976);

3) Depth of coal layer: greater than 12 m. This is a key factor that provides minimum conditions for performing underground coal combustion (Perkins G, 2005);
4) Ash content: not greater that 15% for idealised cases, according to English empirical recommendations. This is for idealised conditions. From the empirical data from coal in the Republic of North Macedonia, it shows ash contents much higher than those permitted, i.e. more than 30%;
5) Sulphur content: not exceeding 5%. The presence of sulphur is one of the main hypotheses (pyrite based) for the initiation of spontaneous combustion in coal;
6) Dip angle (inclination): greater than 5^0. According to research, combustion from the floor toward the roof sections of the coal seam is much easier to perform in steeply inclined seams, particularly from deeper to shallower parts;
7) Structure of the coal seam and the overburden: these are important for understanding the fracturing of the coal seam, as well as the overlying overburden layers. Determining fracture systems and the degree of fracturing are essential for the proper execution of underground combustion. More compact formations result in lower loss of the generated gases;
8) Hydrogeological conditions: the occurrence of groundwater and the permeability coefficient are important factors influencing the presence of water, which plays a key role in underground gasification;
9) Coal reserves, that cannot be mined using conventional exploitation methods at the current level of technological development;
10) Accessibility and infrastructure.

The first 5 criteria are the main criteria on which the model was defined. The remaining criteria are factors that are generally met by all analysed coal deposits which are the subject of this research.

3. Geological profile of coal deposits

3.1. The *Mariovo* coal deposit

The productive coal formation is represented by a single coal seam, which has a subhorizontal position with variable thickness (from 1.3-14.9 m) and a relative occurrence depth of 7,7 to 279 m. (Andreevski, 1995).

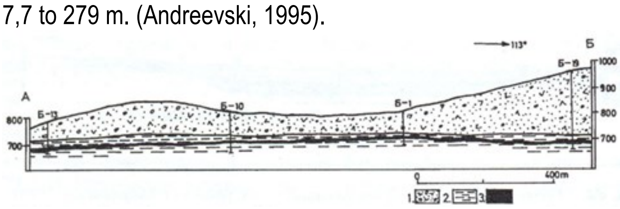

Fig. 1. Restrain geological profile of the *Mariovo* ore deposit 1-volcanic breccias and tuffs, 2-marls, 3-coal (Andreevski, 1995)

The following tables 1, 2, and 3 present the parameters in order of their importance for the correct selection of the location for underground gasification of representative coal deposits.

3.2. Coal deposit PJS in *Suvodol* open pit

The basal coal complex, with a maximum thickness of up to 150 m, is characterised by significant variability and heterogeneity, both in terms of the number of coal seams (1-13) and their thickness (0.60-21.10 m) (Andreevski, 1995).

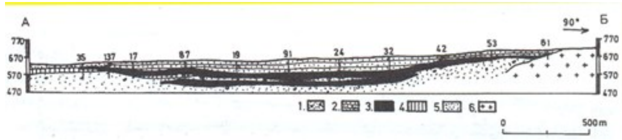

Fig. 2. Characteristic geological profile of the *Suvodol* ore deposit 1-yellow sands and gravels, 2-dry dust and sands, 3-green dry clays, 4-coal layer, 5-underlying sands, dust and coal clay, 6-green sands and dust, 7-gneiss (Andreevski, 1995)

Table 1. *General data of the Mariovo deposit* (Premogovnik Velenje, 2012)

No	Parameter	Requirement
1	Coal rank/type	Dark brown lignite
2	Seam thickness	The thickness of the coal seam ranges from 0.5 m to a maximum of 16.3 m. The average depth of the coal seam is about 7.78 m
3	Seam depth	In the extreme SW parts, it lies at a maximum depth of 268m. The calculated average depth is 116.9 m
4	Seam dip/inclination	The coal seam is sub horizontal, slightly monoclinal from east to west, with a slight dip of 1.3° towards the SW part maximum of 12 ° towards SW direction.
5	Structure of the coal seam	General fault structures with directions of extension N-S and NW-SSE, with a transverse orientation of the Mariovo basin. No local distinctly marked fault structure have been registered in the coal seam.
6	Coal composition in terms of methane gas content and explosiveness	The relative methane abundance ranges from 0.00-0.057 m³/t and the absolute meta-abundance from 0.00-0.059 m³/t. According to the degree of methane (CH_4) hazard, the „Mariovo"deposit is classified in the Methane, I- category. The coal from the "Mariovo" deposit shows explosive characteristics, with the lower limit of explosivity proven at 150 g/m³, and it can be concluded that the coal is self-igniting and belongs to group II.
7	Hydrogeological conditions	Existence of several types of aquifers, a complex compacted karst-fissure type of aquifer with a free groundwater level in the upper coal layer, a compacted type of aquifer with a pressurized groundwater level in the lower coal layer, and aquifer in the coal bed with a pressurized level as well as artesian and sub artesian pressures in the coal bed.
8	Coal reserves	A=30.677.498 B= 32.597.016 C_1= 6.954.525 Total= 70. 289.038 t
9	Access and infrastructure	The communication links to the deposit are good, as there is an asphalt road in good condition. The "Mariovo" deposit is located between the villages of Vitoliste, Polchiste, Beshiste and Manastir, but all settlements are almost completely emty.
10	Socio-economic	If we take into account that about 50 km away is the Prilep town with about 70 thousand inhabitants and a large percentage of unemployed young people, it can be assesed as a positive circumstance in terms of labor force.

Table 2. *Input data of PJS in Suvodol open pit mine* (Rudprojekt, Main Mining Project for the Opening and Exploitation of Coal from the PJS Mine “Suvodol” – Technical Project for Coal Excavation, Book II/3, 2008)

No	Parameter	Requirement
1	Coal rank/type	Dark brown lignite
2	Seam thickness	There are 1-18 coal layers with a total thickness of 0.40 m. The average thickness of the coal layers in PJS is 14.97 m. Two coal layers can be distinguished as economically interesting, namely: I-th coal layer with a relative thickness of 0.80-4.50 m, and II-th main coal layer of 8-13 m
3	Seam depth	I-th bed layer from 2.5 m to 35 m and II-th bed main layer from 50-100 m
4	Seam dip/inclination	The coal seams in the peripheral parts of the deposit, specifically in the northern, southern and eastern parts (around the underground ridge) extend to the metamorphic complex itself, on which they lie directly or emerge and dip towards the central part at an angle of 10-15°.
5	Structure of the coal seam	In the PJS "Suvodol" coal deposit, the existence of structural forms from the fold and rupture tectonics has been established. From the elements of the fold tectonics, the existence of anticlinal and synclinal forms with gentle slopes from 4-8°, which create undulation in the coal seam. From rupture structures, several faults have been established.
6	Coal composition in terms of methane gas content and explosiveness	The relative methane abundance ranges from 0.00-0.42 m³/t and the absolute methane abundance from 0.00-0.59 m³/t. According to the degree of methane (CH_4) hazard, the PJS "Suvodol" deposit is classified in the methane, I-category. The coal from PJS "Suvodol" deposit shows explosive characteristics, with the lower limit of explosiveness proven at 150 g/m³, and it can be concluded that the coal is selfigniting and belongs to the II group.
7	Hydrogeological conditions	In the PJS "Suvodol" deposit are distinguished: roof aquifer, interlayer aquifers and floor aquifer. The roof aquifer extends towards the eastern, northern and northwestern parts of the deposit. The occurrence and level of groundwater at the roof aquifer have been registered in almost all conducted exploratory boreholes and it is generally distinguished as an aquifer with free groundwater. In the interlayer aquifers, the presence of groundwater under pressure (with artesian and sub artesian levels) has generally been registered. In the floor aquifer, the presence of groundwater with quite strong pressures accompanied by the appearance of gases and a regular artesian level has been registerd.
8	Coal reserves	A=42.870.248 BB= 10.594.068 C_1= 1.110.934 Total= 54.525.250 t
9	Access and infrastructure	There is a very good communication link with Bitola town and the village of Novaci with a built asphalt road.
10	Socio-economic	It will enable the improvement of the overall social and economic development of this region in the country.

3.3. The Živojno coal deposit

In the basal facies of the deposit, two coal formations are developed:
- a basal coal formation that lies directly on the paleorelief,
- a productive coal formation, developed in the highest horizons of the basal facies. The formation is represented by a main coal seam, whose thickness is 4-8 m, and several underlying coal seams, which often have productive thickness but without continuity over a larger area. Of particular interest is the productive coal formation, which is developed over an area of about 30 km^2.

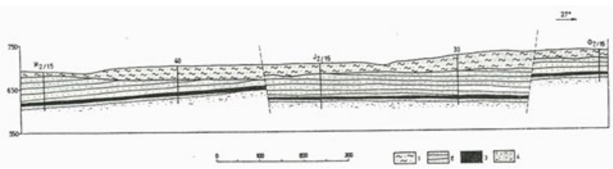

Fig. 3. Geological profile of the *Živojno* ore deposit productive upper lying coal formation, 1- clay, sand formation, 2- aleurite clay, 3-coal, 4-sands and dust (Andreevski, 1995)

Table 3. *Input data of the Živojno deposit* (Rudprojekt, Report on the classification, categorization, and calculation of coal reserves in the "Živojno" coal deposit, 2012)

No	Parameter	Requirement
1	Coal rank/type	Dark brown lignite
2	Seam thickness	The main coal seam has a thickness of 1.10-9.30 m
3	Seam depth	The calculated average depth is 94.9 m, while in some parts a maximum depth of 176.8 m has been determined.
4	Seam dip/inclination	The coal is layered with sub horizontal with a dip angle of 0-15° and locally up to 30° near the fault dislocations
5	Structure of the coal seam	This deposit has a very complex structural and tectonic structure. Generally, several large fault structures with a direction of extension NW-SSE are distinguished, which are parallel to each other and are accompanied by other smaller faults along the entire length. The faulting is expressed by the lowering or raising of discontinuous blocks.
6	Coal composition in terms of methane gas content and explosiveness	The relative methane abundance ranges from 0.01-0.012 m³/t and the absolute methane abundance from 0.004-0.044 m³/t. According to the degree of methane (CH4) hazard, the "Zivojno" deposit is classified in the methane, I-category. The coal from "Zivojno" deposit shows explosive characteristics, with the lower limit of explosiveness proven at 144 g/m³, and it can be concluded that the coal is self-igniting and belongs to the IV group.
7	Hydrogeological conditions	A fractured type of aquifer developed in the impermeable thick deposits in the coal bet – siltstones has also been identified. These semi-petrified rock masses are affected by intensive tectonics, accompanied by two dominant systems of fractures – normal and diagonal to the strata. Unlike "Mariovo", the "Zivojno" deposit has much thicker aquifers both in the bed and in the coal bed.
8	Coal reserves	A (t) / B(t) / C₁(t) For all layers: 26.508.036 / 38.738.004 / 36.438.366 For main layer: 16.605.843 / 29.464.515 / 27.987.491 For other layers: 9.902.193 / 9.273.489 / 8.450.874
9	Access and infrastructure	The communication links to the deposit are good, because there is an asphalt road that is in a good condition. "Zivojno" is located between the villages of Zivojno, Bach and Gemijan, which are inhabited by a predominantly elderly population. If we take into account that the Bitola town is about 30 km away with about 100 thousand inhabitants and a large percentage of young unemployed people, it can be assessed as a positive circumstance in terms of labor force.
10	Socio-economic	Several hundred new jobs will be provided, which will directly affect the improvement of the overall social and economic developments of this underdeveloped region of the country. This could some companies that would indirectly get involved in providing services and goods for operation. A positive moment is that in the vicinity of this deposit are the alredy existing mines "Suvodol" and "Brod- Gneotino", which have a workforce with extensive mining and professional experience.

Based on modern research in this area, 4 main criteria will be selected for these deposits:
- the minimum depth of the coal seam should not exceed 12 m;
- the minimum thickness of the seam should not be less than 2 meters;
- the ash content should not exceed 35%, whereby several variants of each model have been developed with ash contents of 15, 20, 25, 30, and 35%;
- and the sulphur content should be up to 5%.

Besides, 6 criteria that have been selected based on the responses to the questionnaires conducted by mining engineers from the country who works with the exploitation and design of surface coal mines.

By applying appropriate decision-making methods, the most favourable zones for the application of this technology are determined, which will form the basis for the further research and practical implementation.

4. Defining the underground coal gasification model for the selected deposits

The model was analysed based on the input data taken from the Elaboration for detailed geological explorations for Mariovo, PJS in the *Suvodol* and *Živojno* open pit deposits (Premogovnik Velenje, 2012) (Rudprojekt, Main Mining Project for the Opening and Exploitation of Coal from the PJS Mine "Suvodol" – Technical Project for Coal Excavation, Book II/3, 2008) (Rudprojekt, Report on the classification, categorization, and calculation of coal reserves in the "Živojno" coal deposit, 2012). Tabular data were taken from the exploitation boreholes, their elevations on the ground, the depth of occurrence of the coal layers, their strength (thickness), and then ash and sulphur content. Four criteria have been identified that are the main ones for solving the model:

- Criterion K1 – layer depth ≥ 12 m;
- Criterion K2 – layer thickness ≥ 2 m;
- Criterion K3 – ash content ≤ 15% (since lignites in North Macedonia have an ash content ≥ 35%, 5 models were developed with limiting values of ash content of 15, 20, 25, 30, and 35%) (Karanakova Stefanovska, 2017);
- Criterion K4- Sulphur content ≤ 5 %. The remaining 5 criteria are met for almost all deposits and are not subject to modelling.

To solve the model for the *Mariovo* deposit, a selection of exploration boreholes was performed, a total 180 indexed data were used. Some of the data also refer to the same exploration boreholes if at least 2 or more layers of coal appeared on it (Premogovnik Velenje, 2012).

According to five model studies of subvariants of the model with ash contents of 15, 20, 25, 30, and 35% (Karanakova Stefanovska, 2017) for the adopted model with an ash content of 35%, where four criteria are simultaneously satisfied, the percentage of boreholes meeting these criteria is approximately 38% (Karanakova Stefanovska, 2017).

Table 4. *Percentage of file conditions for the Mariovo deposit*

Model	Condition	Fulfilled criteria			
		4	3	2	1
1	K3<=15%	3.33	43.89	97.22	100.00
2	K3<=20%	12.22	55.56	97.22	100.00
3	K3<=25%	23.33	70.00	98.89	100.00
4	K3<=30%	32.78	86.11	98.89	100.00
5	K3<=35%	37.78	91.11	100.00	100.00

Based on the calculations of the quantities of coal that meet the requirements for underground coal gasification, the following data were obtained:

According to the Detailed geological investigation report (Premogovnik Velenje, 2012), ore reserves of category A+B+C_1[1] are 7 026 038 t. The total area of the coal seam is 9 488 371 m^2.

[1] The categories A, B, and C of mineral reserves are used to classify mineral (including coal) reserves according to the degree of exploration, reliability, and accuracy of the data. This classification is defined in accordance with the Law on Mineral Resources of the Republic of North Macedonia

At a coal density of 1.2 t/m³, the average thickness of the coal layer is obtained:

$$d_{sr} = \frac{Q}{\gamma A}\ [m] = \frac{70269038}{1.2x9488371.8} = 6.17\ [m] \qquad (1)$$

where:

Q = 7 026 038 [t] – ore coal reserves from A + B + C_1 category

γ = 1.2 [t/m³] – coal density,

A = 9 488 371 [m²] – area of coal seam.

The area of the part of the coal seam that meets the 4 criteria for underground coal gasification is 2 600 110.03 m². The volume of the coal seam that meets the 4 criteria is 16 046 591.4 m³, or a mass of 19 255 909.7 t.

Of the entire *Mariovo* deposit about 27.40% meet all 4 of the specified criteria for underground coal gasification (Karanakova Stefanovska, 2017). This defines the percentages of the coal seam area (surfaces) that could be exploited and estimates the possible quantities of coal that could be exploited through underground gasification.

The model of PJS in *Suvodol* open pit is solved by selecting the exploration boreholes according to the four given criteria. For this purpose, 785 indexed data were used (Rudprojekt, 2008). According to five model studies of subvariants of the model with ash contents of 15, 20, 25, 30, and 35% (Karanakova Stefanovska, 2017) for the adopted model with an ash content of 35% where four criteria are simultaneously satisfied, the percentage of boreholes meeting these criteria is approximately 6% (Karanakova Stefanovska, 2017).

The results presented in Table 5 are for data from the PJS in the *Suvodol* open pit deposit (Karanakova Stefanovska, 2017).

Table 5. *Percent of file conditions for* PJS in the Suvodol open pit deposit

Model	Condition	Fulfilled criteria			
		4	3	2	1
1	K3<=15%	0.51	32.53	84.69	100.00
2	K3<=20%	1.40	45.03	87.37	100.00
3	K3<=25%	3.44	55.74	91.71	100.00
4	K3<=30%	4.85	64.16	94.64	100.00
5	K3<=35%	5.99	70.03	97.07	100.00

Based on the calculations of the quantities of coal that meet the requirements for underground coal gasification, the following data were obtained: According to the Detailed geological investigation report (Rudprojekt, Main Mining Project for the Opening and Exploitation of Coal from the PJS Mine "Suvodol" – Technical Project for Coal Excavation, Book II/3, 2008), ore reserves of category A+B+C_1 are 54 565 850 t. The total area of the coal seam is 3 292 440.71 m². At a coal density of 1.2 t/m³, the average thickness of the coal layer is obtained:

$$d_{sr} = \frac{Q}{\gamma A}\ [m] = \frac{54565850}{1.2x329440.71} = 13.81\ [m] \qquad (2)$$

where:

Q = 54 565 850 [t] – ore coal reserves from A + B + C_1 category,

γ = 1.2 [t/m³] – coal density,

A = 3 292 440,71 [m²] – area of coal seam.

The area of the part of the coal seam that meets the 4 criteria for underground coal gasification is 504 116.896 m². The volume of the coal seam that meets the 4 criteria is 6 962 303.80 m³, or a mass of 8 354 764.56 t.

Of the entire PJS in the *Suvodol* open pit deposit, about 15% meet all 4 of the specified criteria for underground coal gasification (Karanakova Stefanovska, 2017).

The model of the *Živojno* deposit is solved by selecting the exploration boreholes according to the four given criteria. For this purpose, 48 indexed data were used (Rudprojekt, Report on the classification, categorization, and calculation of coal reserves in the "Živojno" coal deposit, 2012). For the adopted model with an ash content of 35% where four criteria are simultaneously satisfied, the percentage of boreholes meeting these criteria is approximately 79%.

Table 6. *Percentage of file conditions for the Živojno deposit*

Model	Condition	Fulfilled criteria			
		4	3	2	1
1	K3<=15%	18.75	87.50	100.00	100.00
2	K3<=20%	41.67	87.50	100.00	100.00
3	K3<=25%	70.83	91.67	100.00	100.00
4	K3<=30%	79.17	95.83	100.00	100.00
5	K3<=35%	79.17	95.83	100.00	100.00

Based on the calculations of the quantities of coal that meet the requirements for underground coal gasification, the following data were obtained: According to the Detailed geological investigation report (Rudprojekt, Report on the classification, categorization, and calculation of coal reserves in the *Živojno* coal deposit, 2012), ore reserves of category A+B+C_1 are 101684406 t. The total area of the coal seam is 8160261.805 m². At a coal density of 1.2 t/m³, the average thickness of the coal layer is obtained:

$$d_{sr} = \frac{Q}{\gamma A}\ [m] = \frac{101684406}{1.2x8160261.805} = 10.38\ [m] \qquad (3)$$

where:

Q = 101684406 [t] – ore coal reserves from A + B + C_1 category,

γ = 1.2 [t/m³] – coal density,

A = 8160261.805 [m²] – area of coal seam.

The area of the part of the coal seam that meets the 4 criteria for underground coal gasification is 4940752.936 m². The volume of the coal seam that's meets the 4 criteria is 51 305 290.96 m³, or a mass of 61 566 349.16 t. Of the entire *Živojno* coal deposit, about 60.55% meet all 4 of the specified criteria for underground coal gasification (Karanakova Stefanovska, 2017).

The analysis in Chapter 3 on the possibility of Underground coal gasification at the Mariovo, PJS in the *Suvodol* and *Živojno* open pit deposits defines the percentages of the coal seal that could be exploited with gasification. In table 7, a multi-criteria model is presented which, in addition to the percentage share of potential coal reserves suitable for UCG (first criterion), incorporates several other criteria as well (Karanakova Stefanovska, 2017).

Table 7. % of possible coal reserves suitable for UCG

Deposit	Geological coal reserves (A+B+C_1) [t]	Total area of coal seam [m²]	Total area of coal that fullfil conditions for UCG [m²]	Average thickness of coal seam [m]	Predicted amount of coal that can be exploited with UGC	Coal reserve utilization coefficient [%]
Mariovo	70269038	9488372	2600110	6.17	19255910	27.40
PJS in Suvodol	54565850	3292441	504117	13.81	8354765	15.31
Zivojno	101684406	8160262	4940753	10.38	61566349	60.55

5. Selection and identification of criteria for multi-criteria optimisation

Solving the multi-criteria problem involves selecting the “best” alternative from a set of available alternatives, where the term “best” can be interpreted by the decision maker as “most desirable”. Criteria that have the greatest impact on solving the model have been identified. The following 7 criteria have been selected:

- Criterion 1: Coal reserve utilisation coefficient – this criterion is defined and calculated in table 7 (Karanakova Stefanovska, 2017);
- Criterion 2: Dip angle – the basic condition is that it must be at least 5^0 (Shafirovich, 2009);
- Criterion 3: Structural-tectonic characteristics – this criterion is important from the perspective of fracture system and depends on the degree of fracturing (linear, planar, and volumetric). Based on this, a qualitative assessment has also been carried out;
- Criterion 4: Hydrogeological characteristics – the evaluation is based on the permeability coefficient, as well as on the assumed groundwater level;
- Criterion 5: Terrain configuration – this is important from the aspect of the possibility for developing mining operations, i.e. access to the deposit, conditions for further development, road construction, connection to the electrical grid, etc. The evaluation of this criterion is based on visual analysis of satellite images from Google Earth;
- Criterion 6: Cost of exploitation using conventional methods – this criterion is adopted from the Main Mining Projects and techno-economic studies for the respective deposits (Premogovnik Velenje, 2012) (Rudprojekt, Main Mining Project for the Opening and Exploitation of Coal from the PJS Mine “Suvodol” – Technical Project for Coal Excavation, Book II/3, 2008) (Rudprojekt, Report on the classification, categorization, and calculation of coal reserves in the “Živojno” coal deposit, 2012);
- Criterion 7: Possibility of applying conventional methods – the evaluation is based on the feasibility of using conventional methods according to long-term experience.

The multi-criteria model is defined using descriptive assessments which need to be transformed into numerical values. The simplest approach is to use a linear transformation scale.

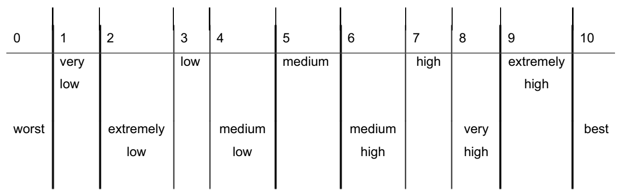

Fig. 4. Linear transformations for the quality attributes

After the transformation of attribute qualities, the input multi-criteria model is obtained, whose solution is carried out using the PROMETHEE II method. The input model prepared for solving with the multi-criteria method is presented in the table 8. After transforming the attribute qualities, table 9 is obtained:

Table 8 Input model for solving with the multi-criteria method PROMETHEE II

No	Multi criteria model	Coal reserve utilization coefficient K1	Dip angle K2	Structural-tectonic characteristics K3	Hydrogeological characteristics K4	Terrain configuration K5	Cost of exploitation K6	Possibility of applying conventional methods K7
		%	deg				EUR/t	
1	Mariovo	27.40	5	High	High	Low	15	Low
2	PJS in Suvodol	15.31	2	Low	Low	High	10.54	High
3	Zivojno	60.55	1.5	medium	Low	Medium high	23.61	Medium
	MIN/MAX	MAX	MAX	MAX	MAX	MAX	MIN	MAX
W	%	50	10	10	5	5	10	10
		0.5	0.1	0.1	0.05	0.05	0.1	0.1

Table 9 Input model after transformation of attribute qualities

No	Multi criteria model	Coal reserve utilization coefficient K1	Dip angle K2	Structural-tectonic characteristics K3	Hydrogeological characteristics K4	Terrain configuration K5	Cost of exploitation K6	Possibility of applying conventional methods K7
		%	deg				EUR/t	
1	Mariovo	27.40	5	7	7	3	15	3
2	PJS in Suvodol	15.31	2	3	3	7	10.54	7
3	Zivojno	60.55	1.5	5	3	6	23.61	5
	MIN/MAX	MAX	MAX	MAX	MAX	MAX	MIN	MAX
W	%	50	10	10	5	5	10	10
		0.5	0.1	0.1	0.05	0.05	0.1	0.1

The following are the results of solving the multi-criteria model using the PROMETHEE II method and the academic version of the VISUAL PROMETHEE software:

Table 10. *Statistical indicator*

Feature	*K1*	*K2*	*K3*	*K4*	*K5*	*K6*	*K7*
MIN	15.31	1.50	3.00	3.00	3.00	10.54	3.00
MAX	60.55	5.00	7.00	7.00	7.00	23.61	7.00
Mean value	34.42	2.83	5.00	4.33	5.33	16.38	5.00
Standard deviation	19.12	1.55	1.63	1.89	1.70	5.42	1.63

Characteristics of the criterion function

The next step is to define the criteria of the criterion function, their type, indifference and preference.

Table 11. *Characteristics of the criterion function*

Features	K1	K2	K3	K4	K5	K6	K7
Min/Max	max	max	max	max	max	min	max
W	0.50	0.10	0.10	0.05	0.05	0.10	0.10
Function type	Ordinary	Level	Level	Ordinary	Level	Ordinary	level
Indifference	-	1.00	1.00	-	2.00	-	1.00
Preference	-	3.00	3.00	-	5.00	-	3.00

Table 12. *Total values according to PROMETHEE II*

Alternative	Phi	Phi+	Phi-
Zivojno	0.3375	0.5625	0.2250
Mariovo	0.1250	0.5250	0.4000
PJS in open pit Suvodol	-0.4625	0.1875	0.6500

Diagrams of the solved model according to the PROMETHEE method

After solving the multi-criteria model, diagrams according to the PROMETHEE method can be drawn.

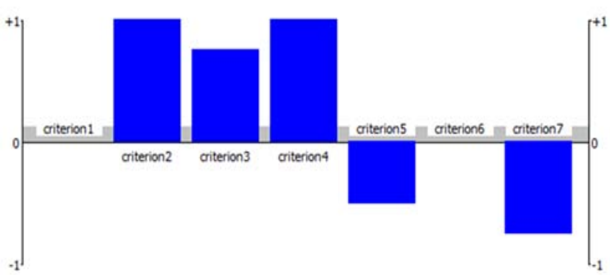

Fig. 5. Diagram of active criteria for alternative 1

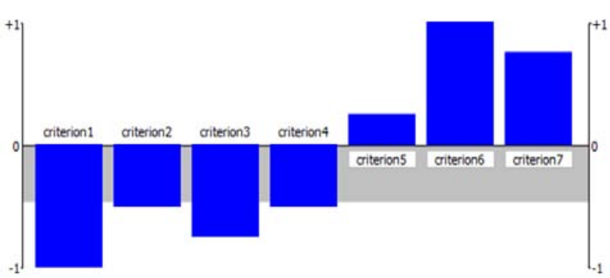

Fig. 6. Diagram of active criteria for alternative 2

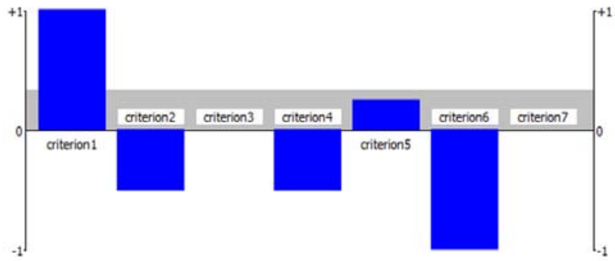

Fig. 7. Diagram of active criteria for alternative 3

The following diagram shows the PROMETHEE – GAIA analysis. GAIA (geometrical analysis for interactive aid) is an interactive geometric representation of the solution from the PROMETHEE method.

Fig. 8. GAIA diagram

From the output tables and diagrams, it can be concluded that the top ranked alternative is Alternative A3: the *Živojno* deposit, with a net flow value of 0.3375.

The results obtained from PROMETHEE II method indicate that the *Živojno* deposit has the highest priority for the implementation of underground coal gasification as an environmentally acceptable method.

Next in the ranking is the *Mariovo* deposit, while the deposit PJS in the *Suvodol* open pit has no priority, with a negative net flow value. This deposit does not show preference toward any alternative and is considered unsuitable for application of underground coal gasification technology.

6. Conclusion

The obtained results from the test model studies of the three coal deposits: *Mariovo*, PJS in the *Suvodol* open pit deposit, and *Živojno*, provide a basis for analysis and decision-making regarding the possible application of underground coal gasification. For this purpose, four main criteria, along with six additional (auxiliary) criteria, were selected for the three considered variant solutions. The selection of criteria was based both on contemporary research in this field and on responses collected through questionnaires completed by mining engineers from the Republic of North Macedonia involved in the exploitation and design of surface coal mines.

The four main criteria are: minimum depth of occurrence of the coal seam (greater than 12 meters), minimum seam thickness (at least 2 meters), ash content (not exceeding 35%), and sulphur content (up to 5%). These four criteria enable the definition of a model used to determine how many of the total number of exploration boreholes satisfy these conditions. The analysis was conducted for five limiting values of ash content: 15%, 20%, 25%, 30%, and 35%. These represent five sub-variant solutions. In this way, for each of the three variant solutions, output tables were generated showing the percentage share of boreholes satisfying 4, 3, 2, and 1 condition(s). For the *Živojno* deposit, analysis shows that the 4 criteria are met by 79.17% of all exploration boreholes (positive and negative), i.e., about 60.55% of the total coal reserves can be exploited with underground coal gasification (Karanakova Stefanovska, 2017).

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