Article

Challenges and Opportunities for End-of-Life Coal Mine Sites: Black-to-Green Energy Approach

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Abstract: This paper presents the possibilities of adapting active mines to generate green energy after their closure using their resources and/or infrastructure. For this purpose, firstly, the temporal horizon of selected mines in Poland was determined, its basic assumption being the analysis of the current state. In the research, 18 mining plants operating within 12 mines in the Upper Silesian Coal Basin (USCB) were analyzed. The analyzed mines belong to three of the five largest hard coal producers in Poland, and the main object of exploitation is hard coal of energy types. Severe restrictions or even abandonment of further investments in the development of the coal mining industry were taken into consideration (regarding the construction of new shafts or the development of new exploitation levels). When determining the temporal horizon, the challenges that hamper the exploitation based at the levels of natural hazards and depth of exploitation in each mine were considered. Secondly, the criteria for the adaptation of active mines to generate energy are presented. The possibility of using the resources and infrastructural potential of active mines to produce geothermal energy from water, extracting coalbed methane (CBM), and processes of underground coal gasification (UCG) are analyzed. Finally, for a selected example—generating energy from underground coal gasification in Polish mine conditions—a structural analysis of the criteria was performed using the MICMAC method, as the Central Mining Institute has an extensive experience in the development of underground coal gasification trials in coal mines. Based on expert analysis and using structural analysis, the criteria important for UCG were selected. As demonstrated in the article, the MICMAC method can be applied in other scenarios with different criteria to implement new technologies in coal mines.

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Keywords: temporal horizon of coal mines; challenges that hamper exploitation; renewable energy; MICMAC method; underground coal gasification (UCG); geothermal energy; coalbed methane (CBM); Upper Silesian Coal Basin (USCB)

1. Introduction

In the 1950s and 1960s, the coal mining industry was an important sector of Western European countries' economies. Hard coal was mined, among others, in Germany [1], the United Kingdom [2], France [3], Spain [4], Belgium [3], and the Netherlands [5]. Since then, coal extraction in EEC countries has been systematically decreasing, and some countries have completely eliminated coal mining—the Netherlands (the 1970s), Belgium (1990s), France (2004), and Spain (2018). Currently, the leading coal producer among the EU countries is Poland, with small amounts still mined in the Czech Republic, Germany, the UK, and Romania [6]. In December 2019, the new growth strategy assumptions were presented in a document titled the European Green Deal for the European Union [7]. The European Green Deal provides an action plan to boost the efficient use of resources by moving to a clean, circular economy [8], investing in environmentally friendly technologies, and decarbonizing the energy sector. One can see that the withdrawal from coal mining

in most Western European countries is a part of the EU climate and energy policy, which assumes achieving climate neutrality in EU countries by 2050 [9]. Zero net greenhouse gas emissions are planned by 2050 with efficient employment of resources along with the transition to a circular economy [2]. The EU established a financial transition support mechanism, called the Just Transition Fund, being a part of the Just Transition Mechanism. The Just Transition Mechanism as a part of the European Green Deal Investment Plan and InvestEU will serve to support projects focusing on both the energy transition and circular economy. Countries applying for the support have to submit “Territorial Just-Transition Plans” to present the justification for obtaining the funds together with the expenditure plan, and to demonstrate how they plan to reach their national climate objectives [10].

The total share of coal in electricity production in Poland in 2018 was 77% [9]. The EU energy policy forces Poland to diversify its energy sources, reducing the demand for coal. Such policy leads to further restructuring of the mining sector, which entails the closure of most mines producing coal for the energy sector, which in most cases takes the form of mine liquidation by filling the shafts and completely cutting off the underground workings from the surface [11]. The consequences of such actions are long term, whereas the entrepreneur continues to bear the costs of both the closure itself and the remedies to the damages suffered as a result of the closure, i.e., costs of pumping mining water, removal of mining damage on the surface, or land reclamation. In order to partly or even completely cover such costs, the business model, formed at the stage when the decision is made to close down a mine, must be adjusted. The model should provide strategies and options enabling the utilization of the remaining resources (coal, gases, water) of the mine as well as its infrastructure (buildings, shafts). Moreover, it should be preceded by a market analysis to determine the profitability of implementing the proposed solutions for the “here and now” scenario and in the longer term.

This article presents both the hazards associated with coal mining and the opportunities for the coal sector. The assessment was made on the basis of mine temporal horizon analysis, understood as the exploitation time with regard to the quantity of resources, and an analysis of the challenges that hamper exploitation in terms of the natural hazards [12]. The main objective of the analysis was to suspend or abandon the investment processes in the mines (new shafts or new exploitation levels), thus keeping operating exclusively within available resources at the available exploitation levels. This approach allows assessing the potential of the mines according to the “here and now” scenario and then transitioning in the new business model. The article presents the potential the infrastructure and/or resources of individual mines offer for production alternatives to classic exploitation, such as energy production, and proposes the criteria to define the possibilities of their adaptation to produce “clean” energy. The article uses the experience of other countries, especially Germany [13,14], Spain [15], and South Africa [16], in mining restructuring. The activities undertaken in this regard should cover a several-year time interval, during which the mines, in addition to their ongoing production, will be able to undertake projects aimed at diversifying their potential into other areas of economic activity. This period will allow minimizing (avoiding) the costs of infrastructure maintenance after the closure, and before the start of the alternative activities.

2. Materials and Methods

The research and analysis were conducted in two research areas. The first specifies the temporal horizon of hard coal mines, while the second specifies the criteria for the alternative, for classic exploitation, use of resources and/or infrastructure of active mines for the production of “clean” energy. The methodology for assessing the temporal horizon of mines was developed with the assumption that the available coal resources would be used and no new investments would be made (such as new shafts or deepening of existing ones, or new exploitation levels). In the proposed methodology, the possibility of using the resources and infrastructural potential of active mines to produce clean energy from geothermal water [17,18], extracting coalbed methane [19–21], and processes

of underground coal gasification [22,23] are shown. The basic criteria determining the possibility of such an undertaking were proposed, based on the literature [24–28] and our own research [12] shown in this paper. For the selected example—underground coal gasification—the results of the structural analysis of the criteria determining the possibility of such use of coal resources are presented. This scenario was selected due to the Central Mining Institute’s extensive experience in the development of two underground coal gasification trials in coal mining, namely, the research and development project HUGE2 (Hydrogen Oriented Underground Coal Gasification for Europe 2) funded by Research Fund Coal and Steel, and the “Elaboration of coal gasification technology for a high efficiency production of fuels and electricity” project funded by the National Centre for Research and Development in Poland.

2.1. Temporal Horizon of Hard Coal Mines

The temporal horizon of the mines was estimated by analyzing both the criteria describing the challenges that hamper the exploitation and the criteria describing the size and the level of the availability of resources. Based on Frejowski et al. [12], the following criteria were analyzed for the assessment of challenges that hamper the exploitation:

- Gas hazard: defined as the number of hazard events related to the ignition and/or explosion of methane in underground workings of the analyzed mines, which occurred in the period from 2008 to 2019 [24,29–32];
- Fire hazard: defined as the number of endogenous fires in the underground workings of the analyzed mines, which took place from 2008 to 2019 [29,30,33–35];
- Rock burst hazard: defined as the number of hazard events related to tremor-associated negative effects in the underground workings of a mine in the period from 2008 to 2019 [29,30,36–39];
- Seismic hazard: defined as the number of high-energy seismic tremors with energies of 10^5 J and higher, which may cause negative effects on the surface, which occurred in the mines in question from 2008 to 2019 [12,30,40,41].

The conducted analysis allowed for the assessment of each mine in terms of the challenges that hamper the exploitation. Those challenges directly affect the cost of mining (the need to maintain the exploitation safety rigors relating to natural hazards) and indirectly affect the temporal horizon of the mine. The results of the above study criteria were subjected to statistical analysis [42,43], as shown in Table 1.

Based on the above analysis, the mines in question were assigned to the following three groups, for simplicity based on the quartiles (lower, median, and upper) obtained as a result of the analysis, defining the level of the challenges that hamper the exploitation:

- Mines with a high risk of hampering exploitation, comprising the mines where the number of hazard events related to natural hazards in the analyzed period was in the third (upper) quartile;
- Mines with an average risk of hampering exploitation, comprising the mines where the number of hazard events related to natural hazards in the analyzed period was in the second (average) quartile;
- Mines with a low risk of hampering exploitation, comprising the mines where the number of hazard events related to natural hazards in the analyzed period was in the first (lower) quartile.

The following criteria were adopted to assess the quality of the resources and the level of the availability of resources [12,44,45].

- Depth of exploitation, defined as the deepest active exploitation level in a mine, based on [29,30,38,46–49];
- Annual coal production, defined as the average annual output of the mine in the period from 2015 to 2019 based on [29,50,51];
- Amount of coal reserves, defined as coal reserves identified in the highest recognition categories, possible to be exploited without undertaking significant investments to

make them available, assuming their use at the level of 30%, based on results of the use of coal deposits in active mines presented in [45,52] and on the size of coal resources in Polish mines based on [53].

Table 1. The result of the statistical analysis of the criteria describing the temporal horizons of mines.

	Seismic Hazard—Number of High-Energy Tremors	Rock Burst Hazard—Number of Rock Bursts	Fire Hazard—Number of Endogenous Fires	Gas Hazard—Number of Methane Ignitions or Explosions	Depth of the Mine—The Deepest Level of Exploitation	Temporal Horizon
Group size	18	18	18	18	18	18
Significance level	0.05	0.05	0.05	0.05	0.05	0.05
Variance	9871.79	3.08	8.87	3.55	37,591.58	132.29
Standard deviation	98.9	1.75	2.97	1.88	193.88	11.5
Coefficient of the variability	1.24	1.5	1.01	1.30	0.24	0.01
Interquartile range	115.25	2	2.75	2.75	250	17
Minimum	0	0	0	0	500	2024
Maximum	346	6	11	6	1150	2062
Lower quartile	3	0	1	0	650	2034
Median	46.5	0	2	0.5	795	2043
Upper quartile	118.25	2	3.75	2.75	900	2051
Skewness	1.49	1.54	1.54	1.22	0.13	0.14
Std. err. of the skewness	0.53	0.53	0.53	0.53	0.53	0.53
Kurtosis	1.819	2.04	1.98	0.68	−0.87	−1.01
Std. err. of the kurtosis	1.037	1.03	1.03	1.03	1.03	1.03

2.2. Alternative Uses of Hard Coal Mines

In the second stage, the analysis was performed to determine the initial possible alternative use of infrastructure/resources of the active mines for the production of “green” energy from mining water/geothermal water, coalbed methane and underground coal gasification. Given the geopolitical situation in Europe, in particular the strong focus on abandoning fossil fuel-based energy production and the emphasis on renewable energy, Poland is forced to take prompt and decisive steps regarding the future of the coal mining sector. This can be achieved in a short time by closing mines—with all the negative environmental, economic, and social and political consequences of this process [54,55]. The decarbonization process may extend over several decades, as was the case in Germany [1,15]. This, however, is not consistent with the EU policy and difficult to implement. It seems that the only rational solution is to transform the mining companies into enterprises operating in other areas of the economy, making use of the infrastructure and resources currently active (available/utilized) in the respective mines. This should reduce the negative effects of decarbonization and will allow mining companies to stay afloat within new business models. The issues of transformation of mining areas are broadly discussed in the world literature, indicating the diversity and wide range of aspects related

to the end of mining and the duration of the decommissioning process of coal mining, as well as its consequences [14,56,57].

2.2.1. Production of Geothermal Energy

The mine's infrastructure, including both underground workings and mine shafts, as well as surface buildings, can be adapted to produce mining water energy. Such solutions are known, among others, in Germany [58], Spain [18,59–61], Canada [62], and the USA [63,64]. Further, in Poland, attempts were made to produce energy from the warm mining water of the closed Saturn mine in the north-eastern part of the Upper Silesian Coal Basin (USCB) and in the active Sobieski mine in the eastern part of the USCB [65]. The issue of geothermal energy resources in the USCB rock mass was discussed, among others, by [66,67]. The potential geothermal water reservoirs in the eastern part of the USCB include thick layers of the Carboniferous sandstone rocks of the Kraków sandstone series and the Upper Silesian sandstone series [68]. The long-term exploitation in the USCB area has resulted in the formation of post-mining goafs, which may also constitute anthropogenic geothermal water reservoirs [67].

For geothermal waters, a temperature range between 20 and a 60 °C is assumed, for which it is possible to use such waters directly in heating systems [66]. In the USCB area, the geothermal gradient varies from 2.0 to 4.5 °C/100 m, and the general downward trend is from the southeast to the southwest of the USCB [69].

For the preliminary assessment of adaptability of active mines to produce energy from warm mining waters, the following criteria were proposed:

- Mine water inflow—defined as the average annual water inflow to the mine. The water inflow to the mine is a value variable with time, and it depends not only on the hydrogeological conditions, but also on the exploitation depth and the size of the extraction. The mines located in the eastern part of the USCB in the Vistula region are characterized by the largest inflow to the mine, with the highest average inflow value of about 60 m³/min occurring in the Sobieski mine [65].
- Mining water temperature—defined as the temperature of rocks at the deepest exploitation level corresponding to water temperature. Mining water pumped to the surface, under conditions of the USCB, typically has a much lower temperature, ranging from 13 to 23 °C [67].
- Mining water quality—defined as the content of mineral substances in mining water (chemistry of mining water). The mineralization of water in the USCB area is variable and depends on the depth and the type of overburden. Generally, it can be assumed that mineralization increases with depth and in regions where the overburden is impermeable and there is no freshwater inflow from the surface. In mining water, apart from large amounts of sulfates and chlorides, also barium and metal compounds can be found, mainly iron and manganese [70], the presence of which may necessitate water treatment, for the proper functioning of the geothermal installation.
- Shaft depth and technical condition—defined as the maximum mine depth resulting from the shaft depth and the maintenance conditions of the shafts (as an effect of age, durability of the used materials, the manner of usage and exploitation conditions). The production of energy from mine waters with the use of mine shafts requires maintenance of the shaft infrastructure. It should be emphasized that the largest number of shafts in history in the area of the USCB were dug in the 1950s, so for at least several dozen years, they have been subjected to the aggressive action of salty groundwater, temperature changes, and rock mass pressure [71]. As a result, the number of shafts that can serve as parts of installation for the production of geothermal energy will be limited.
- Distance to the potential customers—defined as the distance of the shaft from the geothermal energy development sites. It should be as small as possible; hence, it seems reasonable to conduct such projects in highly urbanized areas. According to [72], the optimal distances do not exceed 1000 m.

2.2.2. Energy Production from Coalbed Methane

Coalbed methane (CBM)—a generic term for the methane-rich gas naturally occurring in coal seams typically comprising 80% to 95% methane with lower proportions of ethane, propane, nitrogen, and carbon dioxide. In common international use, this term refers to methane recovered from un-mined coal seams using surface boreholes [20]. It is one of the world's major sources of alternative energy. It is extracted, among others, in Russia, the USA, Australia, China, Canada, and Indonesia [21]. In terms of the method of obtaining methane accompanying coal seams, the following can be distinguished: coalbed methane (CBM)—intact by mining exploitation, treated as the main mineral; coal mine methane (CMM)—methane released during mining, treated as an accompanying mineral; and abandoned mine methane (AMM)—methane from closed mines [20].

In Poland, documented recoverable reserves of coal bed methane are found only in the USCB area (southern part of Poland, Silesia region), and the amount of these resources (as of 31 December 2019) totaled 109,548.53 million m³ [53]. The basic criterion for determining the possibility of producing energy from the coal methane resource is the criterion defined as the amount of methane resources identified for possible rational exploitation.

In assessing the size of recoverable methane, the following criteria should be taken into consideration:

- The thickness of the seams—more than 0.3 m [73];
- The depth of the methane deposit—no more than 1600 m [73];
- The methane content—more than 4.5 m³/Mg_{daf} (Mg of dry ash-free coal) [73].

2.2.3. Energy Production from Underground Coal Gasification (UCG) Process

The first experiments in the area of USCB regarding underground coal gasification (UCG) were conducted in the 1950s in the experimental Mars mine (at that time already part of the Paris mine, closed at the end of 1996) located in the eastern part of the USCB. A research station of the Central Mining Institute in Katowice operated at the mine, and coal gasification experiments were carried out in coal seam no. 808 with the thickness of 1.2 ÷ 1.5 m [44]. In 2014, an underground coal gasification test was carried out in coal seam no. 501 in the now closed Wieczorek mine in Katowice [74], and as a result of the experiment, about 245 Mg of coal was gasified and 1033 million m³ of syngas was obtained [75,76].

The criteria that determine the possibility of conducting the underground gasification of hard coal are presented below:

- The overburden thickness (UCG1), defined as the thickness of the rocks on the coal seam intended for gasification [77];
- The coal seam thickness (UCG2), defined as the minimum average thickness of the coal seam intended for gasification [77];
- The coal ash content (UCG3), defined as the maximum coal ash content [77];
- The sulfur content in coal (UCG4), defined as the maximum content of sulfur and its compounds in coal [77];
- The degree of coalification (UCG5), defined as the dominant type of coal in the bed intended for gasification [77];
- Rock tightness (UCG6), defined as the impermeability of floor and roof rocks in the vicinity of the coal seam [78];
- The deposit fault (UCG7), defined as the number and nature of faults crossing the coal seam to be converted into gas [79];
- The gasification area (UCG8), defined as the size of the plot in the coal seam intended for gasification [27];
- The methane bearing capacity (UCG9), defined as the average methane content in the deposit intended for gasification [80];

- The safe distance (UCG10), defined as the minimum distance of the plot (separated part of the coal seam) intended for gasification from the goaf and underground workings [27].

2.3. MICMAC METHOD

The MICMAC method was applied to develop structural analysis [81,82], based on the results of expert studies on the interaction among the criteria [83,84].

The research was based on the results of surveys carried out using the Delphi method, described in detail by [12,85]. Twenty-eight experts from Poland took part in the survey. The hard coal mining industry was represented by 43% of the experts and the scientific entity was represented by the other 57%. The range of years of experience in coal mining-related activities was from 10 to over 40 years. Experts' competence calculated as K_k [12,85] was in the range 0.5–1.0. Table 2 below shows a summary list of the experts involved in the study.

Table 2. Summary of expert characteristics.

Years of Experience in Coal Mining	Number of Experts from Scientific Entity	Number of Experts from Coal Mining Industry
10–20	6	5
21–30	4	5
31–40	4	2
>40	2	0
Indicator of Experts' Competence	Number of Experts from Scientific Entity	Number of Experts from Coal Mining Industry
0.5–0.6	3	4
0.7–0.8	8	6
0.9–1.0	5	2

With the unsorted list of variables, a group of experts from the Polish coal mining industry and scientific entity will state the influence that each variable has over the rest of the variables of the system. The group will provide an $n \times n$ integer matrix that states these influences, based on the experts' knowledge. With this information, a matrix of direct influence describing the relation of direct influences between the variables defining the system will be developed.

In a systemic vision, a variable does not exist unless it is a part of the relational web with the other variables. In addition, the structural analysis allows connecting the variables in a two-entry table (direct relations). This entry of the matrix is generally quantitative, adjusting the intensities of the relations among the variables.

This phase of entry helps to put forward for n variables $n \times n$ questions, of which some would have escaped without such a systematic and comprehensive reflection. This procedure of questioning allows not only avoiding errors, but also ordering and classifying the ideas by creating a common language. It also provides the opportunity to redefine the variables and thus modify the system's analysis. Further, a brainstorm meeting was organized to use the experts' knowledge to achieve this goal.

Identifying the key variables is the main step of the structural analysis. Some important measures that provide the initial insight into the significance of the variables can be computed from the matrix of direct influence.

Two methods can be applied: the direct method, which estimates the overall direct influence and direct dependence of a variable in the system directly from the matrix, and the indirect method, which estimates the overall influence and dependence of a variable through other variables of the system.

In the direct method, the total of connections in a row indicates the importance of the influence of a variable on the whole system (level of direct motricity). The total in a column indicates the degree of dependence of a variable (level of direct dependence).

With the indirect method, it will be possible to detect the hidden variables thanks to matrix multiplication. This allows studying the diffusion of the impacts by the paths and the loops of feedback, and consequently to sort the variables: by order of influence (considering the number of paths and loops of length $1, 2 \dots n$ resulting from each variable), or by order of dependence (considering the number of paths and loops of length $1, 2 \dots n$ arriving on each variable). Generally, the classification becomes stable after multiplying the matrix by itself 3, 4, or 5 times.

The comparison of the results (direct and indirect classification) obviously enables the confirmation of the importance of certain variables, but also serves to reveal certain variables which, because of their indirect actions, play a dominant role (and which the direct classification did not allow revealing).

Therefore, the comparison of the hierarchy of the variables in the various classifications is rich in information, providing the key variables of the system.

The division into groups of factors is presented in Figure 1 [12,75].

Figure 1. Map of direct influences and dependences between criteria.

There are 4 areas (quadrants) in the figure that define the potential and significance of the criteria (variables) on them.

- The first quadrant (upper right)—variable factors, characterized by both the highest influences on others and the highest degree of dependencies, among which key factors and objective factors can be distinguished. The objective variables depend on them more than the key variables, rather than influencing them by themselves.
- The second quadrant (upper left)—the criteria referred to as the impact factors which are characterized by high impact and, at the same time, a limited relationship (determinant factors—mainspring and barrier) or absence (environmental factors).
- The third quadrant (bottom left)—autonomous factors which do not directly affect the system, and variables of medium and low impact on the equation (second-order factors).
- The fourth quadrant (bottom right)—the criteria having a medium/low influence on the others but medium/high dependence (dependent factors). There are also result factors that have a low impact on others and a high degree of dependence on others.
- Central area of the matrix—it contains regulatory factors that are characterized by both medium influence and medium dependence.

3. Results and Discussion

3.1. Estimated Temporal Horizon of Mines

In the research, 18 mining plants operating within 12 mines in the USCB area were analyzed. The analyzed mines belong to three of the five largest hard coal producers in Poland, and the main object of exploitation is hard coal of energy types. The analyzed mining plants employ over 47,000 people in total and operate in a total area of about 650 km², while their total average annual output is approximately 36 million tons of hard coal, mostly steam coal.

The oldest of the analyzed mines, the ROW mine Rydułtowy plant, began operation at the end of the 18th century, the youngest, the Murcki-Staszic mine, has been in operation since 1964, and the Piast-Ziemowit mine Piast plant has been operating since 1975. The average lifetime of a coal mine is approximately 100 years. Mining works are carried out at a depth of about 400 to over 1200 m, the average depth of mining in 2020 being 800 m. The deepest mining, at a depth of over 1200 m, is carried out by: the ROW mine Rydułtowy plant, Sośnica mine, Murcki-Staszic mine, the Ruda mine Bielszowice plant, and the Ruda mine Halemba plant (at depths over 1000 m).

Considering the criteria related to the mining geo-environment resulting from the structural analysis carried out using the MICMAC method [12], the challenges that hamper the exploitation and the temporal horizon of the mines are presented in Figure 2. The challenges that hamper the exploitation were assessed bearing in mind the hazard events that occurred in 2008 ÷ 2019 and were related to the occurrence of gas, fires, rock bursts, and seismic hazards [29,30]. The temporal horizon of mines was determined on the basis of the balance resources identified in the highest categories [53], taking into account the possibility of their use from all coal resources at the level of 30% [45,52] and the average annual extraction [29].

Figure 2. List of events related to the challenges that hamper the exploitation against the background of the temporal horizon of mines/mining plants, from the authors' study.

Figure 3 presents a collective summary of hazard events related to the mines in question against the background of their deepest exploitation level and their temporal horizons. The hazard levels correspond to the number of hazard events related to gas (methane ignitions and explosions), fire (endogenous fires), seismic (high-energy tremors with energies higher than 10⁴ J), and the occurrence of rock bursts.

The largest number of hazard events in the analyzed period took place in mines with relatively far temporal horizons: Murcki-Staszic mine (20 events—temporal horizon until 2046), the Ruda mine Bielszowice plant (15 events—temporal horizon until 2066), Mysłowice-Wesoła mine (14 events—temporal horizon until 2052), the Ruda mine Halemba plant (10 events—temporal horizon until 2062), and one with a short temporal horizon—the ROW mine Rydułtowy plant (11 events—temporal horizon until 2032). Relatively favorable geological and mining conditions, including the absence of a hazard event with methane and rock burst hazards, characterized the Piast-Ziemowit mine Piast plant (two

events—temporal horizon until 2056), Sobieski Mining Plant (six events—temporal horizon until 2060), and Janina Mining Plant (two events—temporal horizon until 2049).

Mine/mining plant	Deepest exploitation level, m	Gas hazard	Fire hazard	Seismic hazard	Rockburst hazard	The temporal horizon of mine/mining plant
Bolesław Śmiały Mine	530	LOW	LOW	LOW	LOW	2024
Piast - Ziemowit Mine Ziemowit Plant	650	LOW	LOW	HIGH	LOW	2031
ROW Mine Rydułtowy Plant	1150	AVERAGE	AVERAGE	HIGH	HIGH	2032
ROW Mine Jankowice Plant	700	LOW	AVERAGE	LOW	LOW	2034
ROW Mine Chwałowice Plant	550	AVERAGE	LOW	LOW	LOW	2034
Wujek Mine	680	LOW	AVERAGE	LOW	LOW	2035
ROW Mine Marcel Plant	800	LOW	LOW	AVERAGE	HIGH	2036
Bobrek - Piekary Mine Bobrek Plant	840	LOW	LOW	AVERAGE	LOW	2041
Ruda Mine Pokój Plant	790	AVERAGE	LOW	LOW	HIGH	2041
Murcki - Staszic Mine	900	HIGH	HIGH	HIGH	HIGH	2046
Brzeszcze Mining Plant	900	AVERAGE	LOW	LOW	LOW	2048
Sośnica Mine	950	HIGH	AVERAGE	AVERAGE	LOW	2048
Janina Mining Plant	500	LOW	AVERAGE	HIGH	LOW	2049
Mysłowice - Wesola Mine	865	HIGH	HIGH	HIGH	HIGH	2052
Piast - Ziemowit Mine Piast Plant	650	LOW	AVERAGE	HIGH	LOW	2056
Sobieski Mining Plant	500	LOW	HIGH	HIGH	LOW	2060
Ruda Mine Halemba Plant	1030	HIGH	HIGH	HIGH	HIGH	2062
Ruda Mine Bielszowice Plant	1000	HIGH	HIGH	HIGH	HIGH	2066

Figure 3. Summary of the results of analyses concerning the temporal horizon of mines and level challenges that hamper exploitation, from the authors' study.

The average temporal horizon of mines is 24 years, so it can be assumed that after 2040, no more than half of the current mines/mining plants will operate, and this will take place in difficult conditions, with challenges that hamper the exploitation.

Analysis of Figure 3 shows that the temporal horizons of mines with a low level of exploitation-hampering challenges are shorter than those of the mines operating at medium or high levels. It should be emphasized that one of the main factors affecting the challenges that hamper the exploitation is its depth. Mines/mining plants operating at medium depths may extend their temporal horizon by reaching for deeper coal seams; however, this will be associated with the need to invest large funds for drilling new shafts or building new exploitation levels—one of the assumptions of the analysis was to assess the viability based on the current investment potential, without defining far-reaching visions, which are not feasible given the current political and economic conditions. In other words, current investment potential is understood as exploring available resources without investing in future mining exploitation areas, i.e., deeper coal seams.

3.2. Potential Geothermal Energy Production

Figure 4 shows the average inflow to the mines/mining plants and the average primary rock temperatures at the active, deepest exploitation level. The temperature of the primary rock can be identified with the temperature of the water flowing into the underground workings, although in practice it is lower.

Figure 4. Summary of average inflows to mines/mining plants and the primary rock temperature, from the authors' study.

The largest inflow is characteristic of the mines/mining plants located in the eastern part of the USCB, i.e., in the area with a negative geothermal gradient anomaly. The temperature of rocks is largely dependent on the depth of exploitation and increases with its growth.

Producing geothermal energy directly from underground workings offers an interesting option, which in the case of workings located at a depth of about 1000 m would allow drilling boreholes to reach water resources with high temperatures. However, the solution would require the maintenance of the underground infrastructure, including ventilation and drainage, which, given the high cost of such a project in the current energy consumption pattern, would prove economically unreasonable.

3.3. Opportunities for Energy Production from Coalbed Methane

In Poland, documented recoverable coalbed methane (CBM) resources exist only in the USCB area, and the volume of these resources (as of 31 December 2019) in the analyzed mines/mining plants amounted to 19,001.39 million m³ [53]. The largest identified recoverable resources of CBM (methane accompanying coal resources) are in the following mines: Mysłowice-Wesoła mine (6303.49 million m³ CH₄), Brzeszcze Mining Plant (3303.40 million m³ CH₄), and Sośnica mine (2894.16 million m³ CH₄). Smaller amounts of such resources were documented in the Ruda mine Bielszowice plant, Ruda mine Halemba plant, and ROW mine (all plants).

Currently, the largest amounts of methane are obtained from methane drainage at Brzeszcze mine (average 36.6 million m³CH₄/year), Mysłowice-Wesoła mine (average 19.5 million m³CH₄/year), Murcki-Staszic mine (average 14.3 million m³CH₄/year), and Sośnica mine (average 13.2 million m³CH₄/year). In addition to the Ruda mine Bielszowice plant and the Ruda mine Halemba plant, these are also the most promising areas in terms of future CBM energy production in active mines (Figure 5).

Figure 5. Summary of recoverable methane in mines/mining plants in terms of the average amount of methane included in methane drainage, from the authors' study according to [29].

3.4. Possibilities for Conducting UCG and MICMAC Analysis

3.4.1. Possibilities for Conducting UCG

The evaluation of bituminous coal resources in the USCB explored up to 1.000 m has demonstrated that only 10% of it may be gasified underground [23]. Figure 6 presents a list of the occurring types of coal in the analyzed mines. Coal seams of low-energy types (type 31 and 32) are commonly found in coal seams lithostratigraphically belonging to the Krakow sandstone series (coal seams of the 100 and 200 series). They form the basis of the resource base and the object of exploitation in the Piast-Ziemowit mine Piast plant, Piast-Ziemowit mine Ziemowit plant, Sobieski Mining Plant, and Janina Mining Plant, located in the eastern part of the USCB. These mines are characterized by large resources of coal, suitable for underground gasification, although apart from the Piast-Ziemowit mine Ziemowit plant, they have long temporal horizons. Due to mining and geological reasons and the quality of coal (high types of coal, type 33 and 34 or higher), the remaining mines will have a limited possibility of underground gasification.

Figure 6. Types of coal mines in terms of the possibility of their use for the purpose of UCG.

3.4.2. MICMAC Analysis

With the use of the MICMAC software, an analysis of the interactions of criteria affecting the potential use of coal resources in active mines for UCG was performed. The analysis took into account the 10 criteria whose mutual influences were determined by an expert method (described in Section 2.3).

The figure below shows the results of the implementation of the matrix direct influence (MDI) method (Figure 7a) and the matrix indirect influence (MII) method (Figure 7b) for determining the mutual influence and dependence of the criteria. Based on the MDI analysis, it can be observed that UCG10 (safe distance) is the regulatory factor. The impact factors are UCG1 (overburden thickness) and UCG7 (deposit fault), while the result factor is UCG8 (gasification area). The other criteria (autonomous factors) have no significant impact on the system.

The results of the indirect analysis MII (Figure 7b) compared to the results of direct analysis MDI (Figure 7a) show that:

- UCG10 (safe distance) has been transferred from the central area of the matrix (regulatory factors) to the first quadrant (variable factors—key factor).
- UCG8 (gasification area) has been transferred from the fourth quadrant (dependent factors) to the first quadrant (variable factors—objective factor).
- UCG9 (methane bearing capacity) has been transferred from the third quadrant (autonomous factors) to the second quadrant (impact factors).
- UCG2 (coal seam thickness) has been transformed from the third quadrant (autonomous factors) to the central area of the matrix (regulatory factor).

Figure 7. Maps of structural analysis: (a) direct influences/dependences MDI for UCG criterion; (b) indirect influences/dependences MII for UCG criterion.

The figure below shows direct (Figure 8a) and indirect (Figure 8b) influences between the analyzed criteria. The strongest indirect influences (Figure 8b) occur between the impact factor UCG1 (overburden thickness) and the variable factor UCG 8 (gasification area) and between the impact factor UCG7 (deposit fault) and the variable factor UCG8 (gasification area). The relatively strong indirect influences occur between the variable factors UCG10 (safe distance) and UCG8 (gasification area), between the impact factor UCG9 (methane bearing capacity) and the variable factor UCG8 (gasification area), and between the impact factor UCG1 (overburden thickness) and the variable factor UCG10 (safe distance).

Figure 8. Graphs of structural analysis: (a) direct influences/dependences for UCG criterion; (b) indirect influences/dependences for UCG criterion.

Summing up, it can be concluded that the variable factors for the feasibility of UCG, i.e., the objective factor UCG8 (gasification area) and the key factor UCG10 (safe distance), will determine the safety of such a process as well as its technological capabilities. The UCG1 (thickness of the seam) as a regulatory factor may determine the size and location of such plots. The impact factors for the gasification process will be: the environmental factors UCG1 (thickness of the overburden) and UCG7 (deposit fault) and the determinant factor UCG9 (methane bearing capacity)—they have a very strong impact on the feasibility of UCG (so-called mainspring and barrier of the system), but they are very difficult to control. The remaining factors have little effects on the system. Table 3 summarizes the results of the MICMAC structural analysis.

Table 3. Summary of structural analysis using MICMAC.

Quadrant Number	Factors	Matrix Direct Influences Analysis	Matrix Indirect Influences Analysis	Evaluation of Factors on the Possibility of UCG
I	Variable (Key and objective)	-	UCG10 (safe distance)—key factor UCG8 (gasification area)—objective factor	Priority factors for the evaluation
II	Impact (Determinant and environmental)	UCG1 (overburden thickness) UCG7 (deposit faults)	UCG1 (overburden thickness)—environmental factor UCG7 (deposit faults)—environmental factor UCG9 (methane bearing capacity)—determinant factor	Factors determining the evaluation
III	Autonomous	UCG2 (coal seam thickness) UCG3 (coal ash content) UCG4 (sulfur content in coal) UCG5 (degree of coalification) UCG6 (rock tightness) UCG9 (methane bearing capacity)	UCG3 (coal ash content) UCG4 (sulfur content in coal) UCG5 (degree of coalification) UCG6 (rock tightness)	Factors with low influence on the evaluation
IV	Dependent (Result)	UCG8 (gasification area)	-	Factors with high dependency and low impact on the evaluation
Central area of the matrix	Regulatory	UCG10 (safe distance)	UCG2 (coal seam thickness)	Factors with medium dependency and medium impact on the evaluation

4. Conclusions

The temporal horizon of hard coal mines in the USCB area is directly related to the amount of available resources and the average quantity of their annual extraction. It is also dependent on the challenges that hamper the exploitation, characteristic for each mine, resulting from the local geological and mining conditions, including the occurrence and intensity of natural hazards.

The results of the research and analyses have shown that the average temporal horizon of the analyzed mines is 24 years. The temporal horizons of the analyzed mines extend from 2024 to 2066. It has been shown that the level of challenges that hamper the exploitation is relatively low, mainly in mines with a short temporal horizon—in seven of nine mines with a temporal horizon to 2041. In far-temporal horizon mines, this level is usually high. From the analyzed mines, only four have resources with a temporal horizon longer than 25 years with relatively favorable challenges that hamper the exploitation. On the other hand, three of them operate at a shallow depth of less than 650 m. The start of operation at greater depths will be associated with an increased level of challenges—in particular, the gas and rock burst hazards will increase.

Assuming a significant reduction in or even suspension of funds for strategic investments in coal mines, it seems necessary to prepare them, depending on the local

environmental, technical, organizational, and social conditions, to adapt to the alternative of classic exploitation and use of their resource/infrastructural potential in other areas of the economy, especially those related to the production of green energy.

Based on the literature analysis, trends in the global mining and energy industry, and own research, the criteria for the possible use of active mines for the production of renewable energy (including the generation of energy from mine water, energy from coalbed methane, or underground coal gasification processes) were presented.

A structural analysis using the MICMAC method was performed for the criteria, based on the results of surveys carried out using the Delphi method, determining the possibility of conducting the underground coal gasification process. On its basis, the variable criteria for this process were determined, which affect the safety of such a process and its technological capabilities—the size of the gasification area (objective factor) and the safe distance between the gasification area and underground workings/shafts (key factor). Other important factors are impact factors—influencing the entire process. Those comprise the criteria for the thickness of the overburden and the faults in the deposit (environmental factors) and the methane bearing capacity (determinant factor). The thickness of the coal seam should also be regarded as an important criterion as it regulates the size and the location of the gasification area (regulatory factor).

It should be noted that the presented scenarios for the use of active mines were focused on the production of green energy from geothermal water/methane/coal gasification. Similar principles can be applied to other scenarios such as energy from underground pumped hydro storage systems, production of fresh water or industrial salt, and geotourism. As demonstrated in the article, the MICMAC method for underground coal gasification can be applied in other scenarios with different criteria to implement new technologies in coal mines.

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