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Hydraulic Borehole Mining (HBM) technology employed in lignite mining – technical, economic and market aspects

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Keywords

hydraulic borehole mining; HBM; lignite; cost-effectiveness; economic efficiency; dynamic generation cost index

Hydraulic Borehole Mining (HBM) technology employed in lignite mining – technical, economic and market aspects

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Abstract

The results of a cost-effectiveness and economic efficiency assessment of the Hydraulic Borehole Mining (HBM) technology applied to lignite mining are presented. The Dynamic Generation Cost, the Net Present Value, and the Internal Rate of Return were calculated for the extraction of lignite at a rate of about 3.44 million Mg/year from a mining parcel of 1 × 2.5 km, taking into account CAPEX and OPEX. The cost of mining 1 Mg of lignite using the HBM technology was reported to be lower than its market prices before the energy crisis in Europe caused by the war in Ukraine. The values of the NPV and IRR confirm that the HBM technology may be economically effective in lignite mining. The greatest influence on the cost-effectiveness of the HBM technology was caused by the price of backfill and the diameter of the mining cavern. The NPV is affected by changes in lignite prices. The capital expenditures required by the HBM technology have the least impact on the results in contrary to the open-pit mining technology. Lignite mining using the HBM technology is possible at a level similar to the current level of mining by open-pit technology in Polish conditions.

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1. Introduction

Global demand for raw materials is growing rapidly, and mining companies are facing more and more challenges in order to extract them. They are struggling with numerous multidisciplinary problems, taking risks that are increasingly difficult to accept. Safety, ecology, and social aspects significantly increase the costs of new mining investments employing conventional mining methods. Prices of raw materials and useful minerals are constantly on the rising curve, driving the "fever" of the technological competition race. The exploitation of useful minerals deposits, depending on the type of mineral, its shape, form and size of the deposit, as well as geological conditions, especially the depth of the deposit occurrence, is typically carried out by three types of mining methods: underground, open pit or borehole. The variety of borehole methods are mainly implemented for oil, natural gas, and sulphur extraction. Conventional mining methods (open-pit and underground) are time-consuming, require huge capital investments, and are burdened by the risks related to ensuring work safety and preventing environmental damage [1,2]. They have reached the limits of their technological development capabilities. In recent years, there has been significant progress in the development of alternative mining technologies for resource extraction. The leading technology is Hydraulic Borehole Mining, which uses an airlift pump for the vertical transportation of extracted bulk material. It offers a number of important practical advantages compared to conventional open pit and underground mining methods and makes available the mineral deposits that are not presently mined due to geological, technical, environmental, or economic reasons [3–5]. Since mining takes place through a single borehole, no overburden removal or expensive access is required to drive development openings into a

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targeted ore body. Innovative variations of the borehole method (HBM) enable the extraction of uranium ore, rare earth elements, precious stones (diamonds, emeralds, and sapphires), amber as well as coal methane [6–12]. The HBM method of mining solid mineral deposits involves hydraulic mining of the deposit in a borehole using a high-pressure water jet coming out of a monitor nozzle located in a multifunctional mining head called the HBM mining tool [13,14]. The process of the HBM excavation involves a certain set of actions, namely: drilling and completion of the mining well, exploitation of the deposit: excavation and crushing, vertical transportation of the excavated material to the surface (by air-lift), maintenance of the roof layers and liquidation of the post-excavation void [15,16]. The classification of the HBM into four principal technological phases of wells construction, minerals extraction (pay zone development), slurry processing, and pre- and post-works (including preparation of working agents, facilities, assembling and disassembling as well as mine reclamation) as well as a further, detailed classification of the stages in the mineral extraction phase were given by Bondarchuk and Shenderova [17]. They distinguished three groups of the pay zone development: main processes (rocks fracturing, suction, and lifting of the slurry to the surface and to the slurry pump), auxiliary processes (cleaning of slurry intake ports, drilling of a pilot well, maintenance of the mining chambers roof) and the HBM cutting head monitoring (operation modes control and tripping operation and rotation). Numerous experimental studies have been performed on cutting various rocks using a high-velocity jet of water (i.e., water jet) since the 1960s [17,18], testing and analysing the process mechanisms and optimum parameters. These were summarized recently by Dubiński et al. [15]. The efficiency of high-pressure waterjet cutting can be significantly increased with the use of modern cutting heads and nozzles and the use of an air-shroud formed by a jet of compressed air flowing cylindrically out of the nozzle along with the water. Such innovative solutions have been applied by the German company BAUER in a Canadian uranium ore mine (Orano) [9]. Some examples of hydro-cutting method applications considered, except for coal [19] cover its employment to gold field mining, which was tested in a laboratory scale on a rock samples acquired from the Middle Larba field in Tyndiskii district, Amurksaia oblast, Russia, showing the technology to be applicable to Siberian deposits, that cannot be extracted efficiently using conventional methods [20], diamond extraction [3] or a combined extraction of coal and methane [16]. Some researchers focus their efforts on studying the performance and optimization of particular elements of the technology [14], e.g., the airlift pump [21–26].

When the application of the method to lignite deposits is considered the successful experimental attempt in Bełchatów lignite open pit (Poland) in 1985 should be mentioned, aiming at the determination of the best dynamic parameters of the water jet in terms of cutting and crushing of lignite with the use of water pressure of 6.0–7.0 MPa resulting in the effective hydro-cutting of 4–7 m [27]. The initial application of Hydraulic Borehole Mining technology to lignite deposits was reported there in 1985–1988. These tests were performed with the use of water under the pressure of 7.5 MPa, a flow rate of 3.5 m^3/min and nozzle diameter of 5–15 mm, giving the effective hydro-cutting range of 4–4.5 m [15]. However, it should be emphasised that these first successful Polish experiments were aimed at technical and operational activities. There was a lack of in-depth research to understand better the essence of the individual components (processes) of the HBM technology. Filling this research gap was the RFCS-funded HydroCoal Plus project carried out between 2018 and 2023 with a number of aspects studied within the project, including, e.g., the Life Cycle Assessment of the technology employed in lignite extraction was also performed recently [8], proving the technology to be less environmentally burdensome in terms of land use and solid waste generation categories. The authors also claimed the unit processes of borehole drilling, casing, hydro-cutting, and hydro-crushing being of the highest environmental impact in the site-specific technology assessment.

The economic assessment of the HBM technology was performed in 2012 by Kinley Exploration LLC for the Hansen Uranium Deposit located northwest of Canon City, Colorado, showing that a single borehole mining unit could produce approximately 500,000 lbs. (230,000 kg) of U3O8 per year at a cost of USD 27 per lb. U3O8, and by Merlin Diamonds Ltd. and Jet Mining Ltd. for the Merlin diamond mine located in the Northern Territory of Australia which confirmed the economic viability of the HBM technology in the exploitation of deeper zones of the deposits [6]. In addition to the above-mentioned economic analyses, Merlin Diamonds conducted diamond mining at the bottom of depleted open-pit mines. Drilling platforms were located on floating barges, allowing the use of closed-loop water. Unfortunately, the small scale of the venture contributed to the company being acquired by Lucapa Diamonds (www.lucapa.com.au/projects/merlin). Drilling (exploration and geotechnical) is currently underway, the results of which will enable the completion of a mining feasibility study. The mining operation is planned to resume in 2024.

The economic assessment of diamonds production with the use of the HBM technology and other deposits inaccessible with conventional methods was also performed by Beck et al. [3], who showed, among the others, that the capital costs are considerably lower than for a comparable conventional technology (USD 22 million for a two rig configuration giving approximately 500,000 Mg per year of ore resulting in production of approximately 141,000 carats per year) and rates of return are attractive (net present value, NPV-USD 80 million; internal rate of return, IRR-79%). Although the results of the economic analyses are encouraging, to date, no final decision has been made to carry out a borehole exploration programme.

A detailed technical and economic evaluation of the use of the HBM technology for coal mining was given in the study [28]. The HBM technology was analyzed for performance in the thick, shallow coal seams of Wyoming and the steeply pitching seams of western Colorado. The evaluation considered all the aspects of the mining operation for a 20-year mine life, producing 2.64 million tons/year. The aggregate of the present values of all capital investments occurring at different times of the mine life was estimated, which includes initial capital equipment, construction, land acquisition, working capital, interim equipment replacement, etc. With a desired discounted cash flow rate of return, the annual cash flow, which consists of net profit, depletion, and depreciation, was calculated. On this basis, the minimum selling price of coal was calculated, which guarantees the economic viability of the investment. An economic assessment of the use of the HBM technology to extract various minerals (phosphate, uranium, and oil sands) was presented by [12]. In the case of phosphate mining, a profit after taxes per unit of product equal to 9.35 USD was obtained. Also, in the case of uranium and oil sands mining, the results of the economic analysis were profitable. Based on the promising analytical results, US researchers conducted a number of borehole tests confirming the feasibility of the HBM phosphate mining and presented the results in a report [12]. Unfortunately, due to declining raw material prices and the discovery of shallow deposits, further research into the development of the HBM technology was stopped.

The study presented in this paper fills the research gap related to the development and implementation of the HBM technology in lignite mining by giving the preliminary economic and market assessment of the technology discussed.

2. Materials and methods

2.1. Analyzed HBM production process at mine scale – characteristics of the main technical and economic assumptions

A preliminary assessment of the feasibility of using the HBM technology to extract lignite was carried out based on the HBM production process designed at an industrial scale within the Pilot and Demonstration project HydroCoal Plus [29]. The concept assumes the extraction of about 3.44 million Mg of lignite per year from a mining parcel of 1×2.5 km, delineated on a lignite deposit with a thickness of 20 m. The parcel was divided into 50 mining fields with dimensions of 100×500 m. The adopted scheme of the mining concept is shown in Figure 1.

The following technical parameters of the lignite mining process using the HBM technology were adopted:

- overburden thickness: 40 m,
- lignite seam thickness: 20 m,
- cavern radius calculated from the edge of the mining well: 5 m,
- mining well diameter: 0.60 m,
- mining technology: without protective pillars, with backfilling of selected pits,
- extraction capacity from 1 extraction well: 150 Mg/h.

Mining is assumed to be carried out simultaneously from two directions: from the outside to the inside of the mining parcel. The mining process on each side of the mining parcel is divided into the following stages:

- stage 1: drilling and casing of 0.60 m diameter wells in a row of 8 wells,
- stage 2: installing a multi-purpose mining equipment (mining, crushing, hauling, and backfilling) in every second well,
- stage 3: bringing pipelines (water, air, excavated material, backfill) to the exploited wells,
- stage 4: exploitation of every second mining well with transport of excavated material by pipelines to the settling pond,
- stage 5: backfilling of depleted mining wells,
- stage 6: dismantling of pipelines and mining equipment and installing them on the next four excavated mining wells.

After the above six stages are completed, the extraction process is repeated for the next row of planned wells.

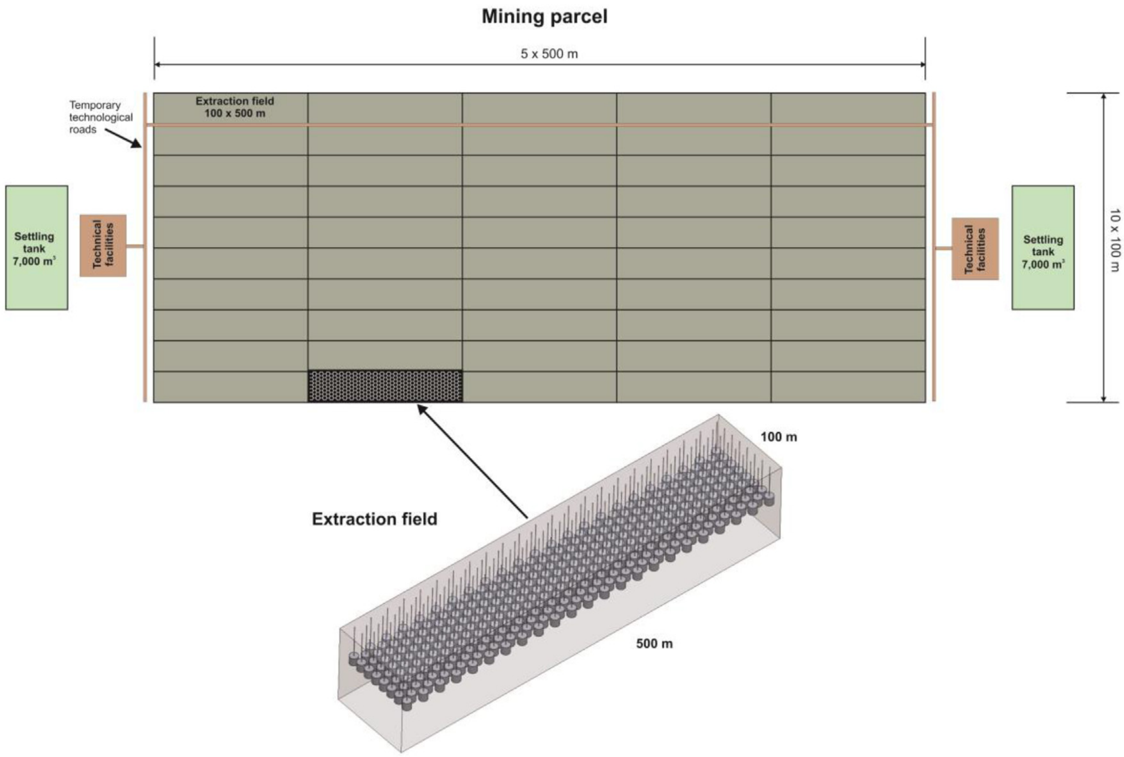

Fig. 1. Schematic of lignite mining concept using HBM technology.

The excavated lignite from the mining equipment is transported by pipelines to the settling tanks and then, after partial dewatering, by conveyor belts to the customers' reception area. The water from the dewatering of the mined lignite in the settling ponds is recycled and reused. The caverns are filled with backfill after lignite extraction. The backfill is delivered by conveyor belts to the vicinity of the mined field and then by pipelines to the empty caverns. Table 1 summarizes the main technological assumptions of the analyzed lignite mining process using the HBM technology.

The process of preparing to mine on the analyzed mining parcel includes:

- supply of electricity,
- supply of water for replenishment of its losses in the mining circuit,
- construction of temporary access roads,
- construction of 2 settling tanks for excavated lignite with a capacity of 7000 m^3 each (providing reception of spoil from 4 mining wells) together with a leachate tank and a pump and filter unit,
- development of 2 mobile compressors (compressed air) and two mobile pumping units (water),
- development of 2 containers with social rooms for employees and two control rooms for the extraction process,
- construction of 2 yards for storage of materials and equipment.

Table 2 summarizes the estimated material outlays and the capital expenditures (CAPEX) necessary to start lignite mining from the analyzed mining parcel.

In addition, with the continuation of extraction at additional extraction fields, it will be necessary to supplement the technical infrastructure in terms of roads, power connections and pipelines. Table 3 summarizes these expenditures by price level for year 2 of the analysis and indicates the frequency with which they will be incurred.

The operating expenditures (OPEX) of the lignite mining process using the HBM technology were estimated taking into account the assumed technological parameters presented in Table 1 and current market prices. In addition, it was assumed that the transport of mined lignite after draining in the settling ponds will be carried out by an overland conveyor system at a distance of 5 km to the point of transshipment to rail transport. From such a distance, backfill will also be delivered by the overland

Table 1. Main technological assumptions of the analyzed process using HBM technology.

Item	Unit	Value
Length of the extraction field	m	500
Width of the extraction field	m	100
Thickness of the lignite seam	m	20
Radius of the mining cavern	m	5
Number of wells in 1 extraction field	pcs.	360
Number of wells in 1 row	pcs.	8
Number of rows of wells in 1 extraction field	pcs.	45
Number of wells extracted simultaneously	pcs.	8
Number of wells extracted during 1 year	pcs.	1826
Extraction capacity with simultaneous operation of	Mg/h/well	130
8 extraction wells	Mg/well	1884
	Mg/year	3,440,348
Preparation time of 1 extraction wells	days	2
Time of exploitation and backfilling of 1 well	days	1
Operating time of 1 extraction field	days	69
Number of working hours – loaders	h/day	16
Number of working hours – piling rig	h/day	8
Number of working hours – cranes	h/day	8
Number of working days per year	days/year	350
Water – demand for 1 extraction well	L/min.	650
Water – losses in the technological circuit	%	20%

conveyor system (conveyor belts). Table 4 summarizes the assumed demand for workers, services, materials, and energy and shows the estimated operating costs for year 2 of the analysis.

2.2. Methods

2.2.1. Cost-effectiveness and economic efficiency assessment

Lignite is one of the main fossil fuels used to generate electricity in Poland. Despite the increasing share of electricity from renewable sources, this situation will remain for many years to come. Indeed, the process of moving away from fossil fuels in the power industry is very costly and long-term. Therefore, it is necessary to consider all technical solutions that can reduce the cost of its extraction and eliminate the negative environmental impact of open-pit lignite mines. At the same time, it is necessary to take into account the significant volatility of market prices of energy resources in the world. Therefore, evaluation of the cost-

Table 2. Summary of the estimated material outlays and the capital expenditures necessary to start lignite mining from the analyzed mining parcel.

Item	Unit	Value	Unit cost		Total cost EUR
Technical and environmental documentation, permits and administrative decisions	set	1	1,400,000	EUR/set	1,400,000
Settling tanks with a capacity of 7000 m^3, in set with a leachate tank and a pump and filter unit	pcs.	2	220	EUR/m^2	1,540,000
Technical facilities	set	2	460,000	EUR/set	920,000
Temporary access roads	m^2	36,000	20	EUR/m^2	720,000
Electricity connection	pcs.	2	430,000	EUR/pcs.	860,000
Water connection	pcs.	2	100,000	EUR/pcs.	200,000
Cranes	pcs.	2	480,000	EUR/pcs.	960,000
Wheel loaders	pcs.	4	220,000	EUR/pcs.	880,000
Air compressors with electrical power of 160 kW	pcs.	2	110,000	EUR/pcs.	220,000
Pump units with electrical power of 400 kW	pcs.	2	760,000	EUR/pcs.	1,520,000
Pipes for piping of extraction wells with a diameter of 7 5/8″	rm	400	50	EUR/m	20,000
Extraction equipment with a set of accessories	set	8	250,000	EUR/pcs.	2,000,000
Piling rig	pcs.	1	3,300,000	EUR/pcs.	3,300,000
Compressed air supply pipelines	m	2000	70	EUR/m	140,000
Water supply pipelines	m	2000	70	EUR/m	140,000
Backfill supply pipelines	m	2500	90	EUR/m	225,000
Excavated lignite discharge pipelines	m	2500	110	EUR/m	275,000
Contingency reserve – 10% of CAPEX	–	–	–	–	1,392,000
Total	–	–	–	–	16,712,000

Table 3. Supplementary material outlays and capital expenditures.

Item	Unit	Value	Unit cost		Total cost EUR
Temporary access roads – every year	m^2	30,000	20	EUR/m^2	600,000
Compressed air supply pipelines – every 4 years	m	1000	70	EUR/m	70,000
Water supply pipelines – every 4 years	m	1000	70	EUR/m	70,000
Backfill supply pipelines – every 4 years	m	1500	90	EUR/m	135,000
Pipelines discharging extracted lignite – every 4 years	m	1500	110	EUR/m	165,000
Water and electricity supply – every 4 years	set	2	110,000	EUR/set	220,000
Total – every year					600,000
Total – every 4 years	–	–	–	–	1,260,000

effectiveness and economic efficiency of using the HBM technology to mine lignite was done using the Dynamic Generation Cost (DGC) index [30–32] and, additionally, the Net Present Value (NPV) and the Internal Rate of Return (IRR) [33,34].

DGC is equal to the price to generate discounted revenues equal to discounted costs. DGC shows the technical cost of obtaining a unit of product, in this case 1 Mg of lignite. Equation (1) was used to calculate the DGC ratio:

$$DGC = \frac{\sum_{t=0}^{n} \frac{CE_t + OE_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{P_t}{(1+i)^t}} \quad (1)$$

where:

CE_t – CAPEX incurred in the year,

OE_t – OPEX incurred in the year,

P_t – the volume of lignite extraction in a given year,

i – discount rate,

t – year, takes values from 0 to n, where 0 is the year in which the first costs are incurred, while n is the last year of mine operations.

The NPV indicator allows for determining the current value of cash inflows and outflows related to the realization of analysed investment. The result is obtained in monetary units, and the following equation (2) was used to calculate it:

$$NPV = \sum_{t=0}^{n} \left(NCF_t \times \frac{1}{(1+i)^t} \right) \quad (2)$$

where:

NCF_t – annual project cash flow in years $t = 0, 1, 2, 3 \ldots n$.

The IRR is the interest rate at which the updated value of cash flow is equal to the current value of cash flow. This is the interest rate at which the net present value of the analysed investment is equal to zero ($NPV = 0$). The IRR, therefore, directly shows the profitability rate of the investment under analysis. The IRR is calculated from equation (3):

$$\sum_{t=0}^{n} \left(NCF_t \times \frac{1}{(1+i)^t} \right) = 0 \quad (3)$$

DGC, NPV, and IRR analyses of the use of the HBM technology for lignite mining was performed

Table 4. Technological assumptions and operating costs of the lignite mining process using HBM technology.

Item	Unit	Value	Unit cost		Total cost	
Service employees (3-shift work system)	post	60	1700	EUR/month	1,224,000	EUR/year
Water – demand per 1 extraction well	L/min	130	2.20	EUR/m^3	189	EUR/extraction well
Electricity – demand per 1 extraction well	kW/hour	140	0.30	EUR/kWh	462	EUR/extraction well
Backfill – demand per 1 extraction well	m^3	1570	8.50	EUR/m^3	13,345	EUR/extraction well
Fuel – cranes	L/1 h of work	40	1.50	EUR/L	336,000	EUR/extraction field
Fuel – loaders	L/1 h of work	90	1.50	EUR/L	3,024,000	EUR/extraction field
Fuel – piling rig	L/1 h of work	80	1.50	EUR/L	336,000	EUR/extraction field
Plastic pipes for casing the wells	m/extraction well	5	40	EUR/m	200	EUR/extraction well
Nozzles (cutting and crushing)	pcs./extraction well	2	40	EUR/pcs.	80	EUR/extraction well
High-pressure hoses – water	pcs./10 extraction wells	1	2200	EUR/pcs.	220	EUR/extraction well
High-pressure hoses – air	pcs./10 extraction wells	1	700	EUR/pcs.	70	EUR/extraction well
Ongoing maintenance, repairs	EUR		430,000	EUR/year	430,000	EUR/year/extraction field
Taxes and fees, administrative costs	%	10%	–	–	2,000,000	EUR/year
Transportation of excavated lignite from the settling tanks to the reception site and backfill from the delivery site to the mining field (includes CAPEX and OPEX of overland conveyor system)	km	5	–	EUR/Mg/5 km	0.80	EUR/Mg

at constant prices. This avoided errors due to the uncertainty associated with available inflation forecasts. For this reason, a discount rate of 5% was used in the calculations, as recommended by the European Commission for analyses at constant prices [35]. The period of analysis includes the total exploitation of the 1 × 2.5 km mining parcel adopted for the calculation, i.e., one year of investment preparation and ten years of operation. The following cost items were considered for the calculation of the DGC, NPV and IRR ratios:

- preparatory costs: technical and environmental documentation, permits and administrative decisions,
- capital expenditures for construction of infrastructure and purchase of equipment and devices necessary for mining,
- capital expenditures for complementary infrastructure during the transfer of operations to subsequent mining fields,
- mining-related operating costs: salaries, water, electricity, backfilling, fuel, plastic pipes for piping the openings, nozzles (cutting and grinding), high-pressure hoses – water, high-pressure hoses – air, ongoing maintenance, repairs, taxes and fees, administrative costs,
- costs of transporting lignite and backfill between the mining site and the site of transshipment to rail transport.

In subsequent years of the analysis, supplementary capital expenditures presented in Table 3 and operating costs presented in Table 4 were adjusted by the price growth rates of energy, salaries, materials, and services. Due to the lack of a current long-term macroeconomic analysis for Poland, the own assumptions, including a forecast of lignite prices, salaries increases, and material and service price increases, were adopted, which were developed on the basis of the most up-to-date studies and publications available [36–39].

2.2.2. Sensitivity analysis

The obtained results of the cost-effectiveness analysis were subjected to a sensitivity analysis. The purpose of the sensitivity analysis is to determine the impact of changes in selected input variables of the account on the level of the cost-effectiveness index of the analyzed HBM technology applied to lignite mining. First, the expected value of this indicator, which is the most realistic under the given conditions of investment uncertainty, is calculated. Then, the changes in the values of successively selected variables are introduced, and the strength and direction of the influence of these variables on the level of efficiency are studied. Each input variable can change by a certain number of percentage points above or below the expected value while keeping the other conditions unchanged. In addition, a new value of the DGC and NPV indexes is calculated for each of these changed quantities, compared to the baseline scenario. The scope of the analysis is limited to those variables that have the greatest impact on the outcome, i.e., the value of the DGC index. These are the so-called critical variables [31,40]. The following critical variables identified for the analyzed HBM technology used for lignite mining were analyzed:

- changes in capital expenditures,
- changes in electricity and fuel prices,
- changes in backfill prices,
- changes in the radius of the mining cavern,
- changes in the thickness of the lignite seam,
- changes in the distance of transport of excavated lignite and backfill by belt conveyors,
- changes in lignite market prices (only by NPV's calculation).

Deviations of ±10%, ±30%, and ±50% were analyzed for all critical variables.

3. Results and discussion

3.1. Results of cost analysis

DGC, NPV, and IRR ratios were calculated on the basis of CAPEX and OPEX presented in the previous chapters of the paper. The purchase price of lignite by utility thermal power plants in Poland in 2021 published in the report [41] and the forecast of lignite price from new deposits published in the paper [38] were used to calculate the revenue. Cash flows for the one-year investment realization period and 10-year exploitation period and the results of analyses are presented in Table 5.

Based on the cash flows presented in Table 5 and the assumed lignite output of 3,440,348 Mg/year, a DGC cost-effectiveness value of EUR 13.84/Mg was obtained. The result of the DGC analysis was related to lignite prices offered by lignite mines in the US and the purchase price of lignite by utility thermal power plants in Poland in 2021. The average annual sale price of lignite at mines by the main rank of coal in 2021 per short ton was 20.10 USD [42], i.e., about 20 EUR/Mg. However, the average purchase price of lignite in Poland in 2021 was 77.50 PLN/Mg, i.e. about 16.97 EUR/Mg. This means that lignite mining using the HBM technology is

Table 5. Cash flows for the DGC, NPV, and IRR ratios calculation of the lignite mining process using HBM technology and results of analyses.

Year of analysis	1	2	3	4	5	6	7	8	9	10	11
CAPEX for construction of infrastructure and purchase of equipment and devices necessary for mining mln EUR	16.712	0	0	0	0	0	0	0	0	0	0
CAPEX for complementary infrastructure during the transfer of operations to subsequent mining fields – pipelines, power supply mln EUR	0	0.600	0.621	0.643	0.665	0.689	0.699	0.709	0.720	0.731	0.742
CAPEX for complementary infrastructure during the transfer of operations to subsequent mining fields – roads, places mln EUR	0	0	0	0	0.732	0.0	0.0	0.0	0.792	0.0	0.408
OPEX – electricity and fuel mln EUR	0	4.540	4.767	5.005	5.255	5.518	5.628	5.741	5.856	5.973	6.092
OPEX – backfill mln EUR	0	24.368	25.221	26.104	27.017	27.963	28.382	28.808	29.240	29.679	30.124
OPEX – transport of lignite and backfill by belt conveyors mln EUR	0	5.505	5.697	5.897	6.103	6.317	6.411	6.508	6.605	6.704	6.805
Other OPEX mln EUR	0	5.039	5.198	5.361	5.529	5.703	5.782	5.862	5.943	6.026	6.109
TOTAL – CAPEX + OPEX mln EUR	**16.712**	**40.052**	**41.503**	**43.009**	**45.302**	**46.189**	**46.903**	**47.628**	**49.156**	**49.112**	**50.280**
Extraction, mln Mg	0	3.440	3.440	3.440	3.440	3.440	3.440	3.440	3.440	3.440	3.440
Unit selling price of lignite, EUR/Mg	–	16.97	16.79	16.61	16.43	16.25	16.07	16.07	16.07	16.07	16.07
Revenue from lignite sales mln EUR	0	58.383	57.763	57.144	56.525	55.906	55.286	55.286	55.286	55.286	55.286
Cash flows mln EUR	**−16.712**	**18.331**	**16.260**	**14.136**	**11.223**	**9.717**	**8.383**	**7.658**	**6.130**	**6.174**	**5.007**
Discounted costs, mln EUR	**386.170**										
Discounted extraction mln Mg	**27.904**										
DGC, EUR/Mg	**13.84**										
NPV, mln EUR	**70.7**										
IRR, %	**97**										

profitable under the calculation assumptions and with a minimum sales price in the entire analyzed period not less than the market prices valid before the energy crisis in Europe caused by the war in Ukraine. The calculated values of the NPV and IRR indicators also confirm that the HBM technology used for lignite mining can be economically effective.

3.2. Sensitivity analysis

Table 6 shows the results of the sensitivity analysis. They show how the identified critical variables affect the obtained values of the DGC and NPV indexes.

In order to interpret the results of the sensitivity analysis and determine the hierarchy of the impact of each critical variable on the cost-effectiveness of using the HBM technology for lignite mining, a graphical interpretation was carried out (see Figs. 2 and 3).

The results of the sensitivity analysis allow the determination of the following hierarchy of impact of the individual determinants on the DGC index calculated for the use of HBM technology for lignite mining (from the highest to the lowest):

Table 6. Results of sensitivity analysis of the use of HBM technology for lignite mining.

Item	Unit	Value of DGC index						
Deviation from the initial value	%	−50%	−30%	−10%	0%	10%	30%	50%
Changes in CAPEX	EUR/Mg	13.54	13.66	13.78	13.84	13.90	14.02	14.14
Changes in electricity and fuel prices	EUR/Mg	13.06	13.37	13.68	13.84	14.00	14.31	14.62
Changes in backfill prices	EUR/Mg	9.84	11.44	13.04	13.84	14.64	16.24	17.83
Changes in the radius of the mining cavern	EUR/Mg	19.13	15.67	14.17	13.84	13.58	13.00	12.68
Changes in the thickness of the lignite seam	EUR/Mg	17.46	15.39	14.24	13.84	13.50	13.00	12.63
Changes in the distance of transport of lignite and backfill by belt conveyors	EUR/Mg	12.94	13.39	13.61	13.84	14.06	14.29	14.74
		Value of NPV index						
Changes in CAPEX	mln EUR	79.8	76.2	72.6	70.7	68.9	65.3	61.6
Changes in electricity and fuel prices	mln EUR	92.6	83.8	75.1	70.7	66.4	57.6	48.9
Changes in backfill prices	mln EUR	182.2	137.6	93.0	70.7	48.4	3.9	−40.7
Changes in the radius of the mining cavern	mln EUR	−34.0	13.5	57.4	70.7	82.3	118.7	143.5
Changes in the thickness of the lignite seam	mln EUR	−15.1	19.3	53.6	70.7	88.1	122.3	156.6
Changes in the distance of transport of lignite and backfill by belt conveyors	mln EUR	95.9	83.3	77.0	70.7	64.4	58.1	45.6

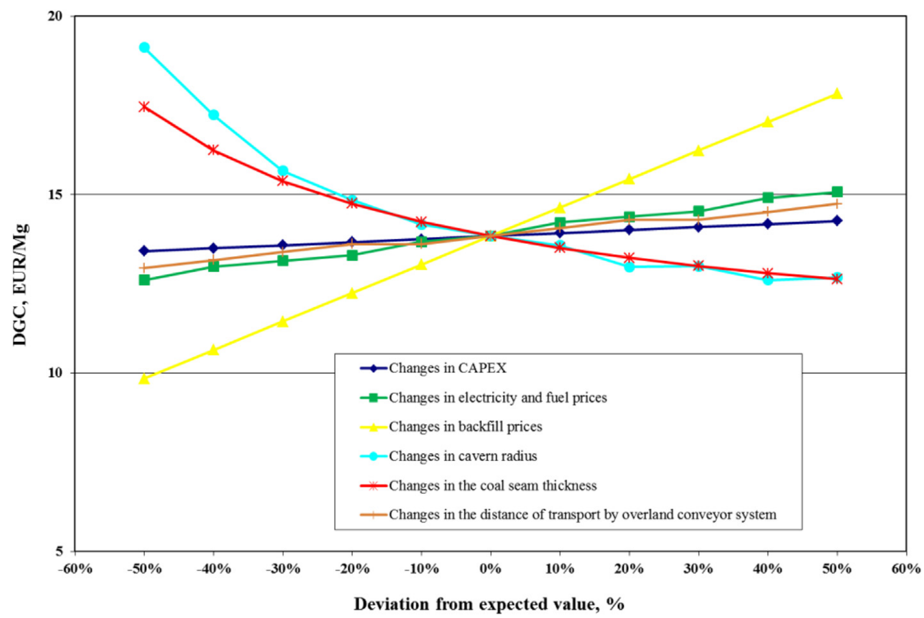

Fig. 2. Graphical interpretation of the results of sensitivity analysis for the use of HBM technology for lignite mining – DGC index.

– backfill prices,
– cavern radius,
– lignite seam thickness,
– electricity and fuel prices,
– distance of transport by overland conveyor system,
– CAPEX.

The above hierarchy results from the fact that the cost of backfilling (without the cost of its transport by overland conveyor system) accounts for as much as 60% of the total operating costs. In addition, the annual cost of the backfill (without the cost of its transport by belt conveyor) is almost 1.5 times the initial capital expenditure. This means that if a cheaper backfill material is used (e.g., the accumulated overburden from depleted open-pit mines in the vicinity of mined lignite deposits), a significant reduction in the cost of lignite production can be achieved using the HBM technology. Another

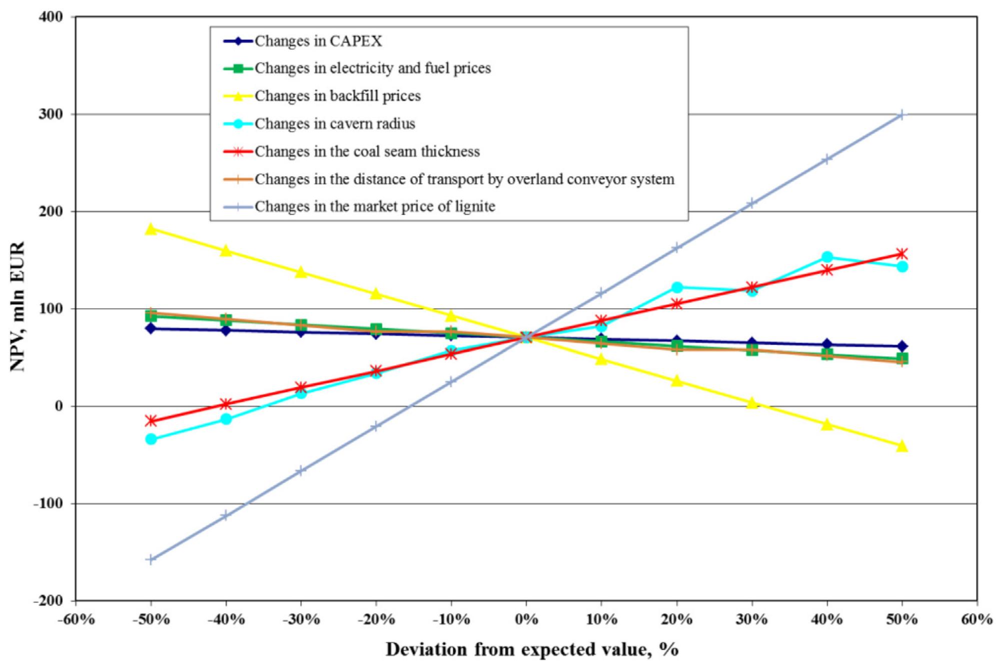

Fig. 3. Graphical interpretation of the results of sensitivity analysis for the use of HBM technology for lignite mining – NPV index.

important factor that has a significant impact on the value of the DGC rate is the diameter of the exploited cavern: increasing the cavern radius results in a slight reduction in mining costs. In contrast, decreasing the radius of the mining cavern has a much greater negative impact on mining costs. This shows that it is possible to reduce mining costs by properly designing the mining parcel and mining field. Initial capital expenditures have the least impact on the DGC index. This is the biggest advantage of using the HBM technology instead of open-pit mines. In the case of open-pit mines, huge amounts of overburden must be removed before mining can begin. This is time-consuming (can take up to a decade), very expensive, and leads to irreversible damage to the earth's surface. For example, the average annual extraction of lignite in recent years has been about 40–42 million Mg at the Bełchatów Mine [43]. To achieve such results, an average of more than 120 million m^3 of overburden has to be removed annually, and about 270 million m^3 of water has to be pumped out. When using the HBM technology, these problems are practically non-existent.

In the case of the NPV indicator, the hierarchy of the impact of critical variables on its value is as follows (from the highest to the lowest):

- market prices of lignite,
- backfill prices,
- cavern radius,
- lignite seam thickness,
- distance of transport by overland conveyor system,
- electricity and fuel prices,
- CAPEX.

Changes in market prices of lignite have the biggest impact on the economic efficiency of using the HBM technology for lignite mining. It should be noted that even a small decrease in market prices (by approximately 15.5% in relation to the adopted assumptions) makes the investment unprofitable. The impact of the remaining critical variables on the value of the NPV indicator is very similar to the impact on the value of the DGC indicator.

3.3. Market opportunities for the application of HBM technology in Polish conditions

Lignite resources in the world are concentrated in several countries. In addition to Poland, this group includes Australia, China, the Czech Republic, Greece, Germany, Russia, the United States, and Turkey. World recoverable lignite resources are estimated at 512 billion Mg [44]. At current production levels, exploitation of these resources will be possible for the next 400 years. This means that the development of new lignite mining technologies using the HBM method makes market sense – over such a long period of time, it will be possible to both refine it and bring it to utility on a commercial scale and then implement it widely.

Based on available data [45], it was determined that lignite mining in Poland has been stable for years at around 60 million Mg/year. Only in 2019–2021, there was a slight decrease in output compared to previous years. Comparing the volume of lignite extraction in 2021 (54.85 million Mg) to its balance resources (23,142.92 million Mg as of the end of 2021), it can be estimated that exploitation of this energy resource at this level will be possible for the next 422 years. This means significant opportunities to apply the HBM technology to lignite mining in Poland in the future. Moreover, comparing the capacity of the analyzed mining field (3.44 million Mg/year) to Poland's annual lignite output in 2021 (54.85 million Mg), it can be calculated that the simultaneous exploitation of 16 mining fields of 100×500 m each would be sufficient to cover Poland's full demand for this raw material. The total area of these 16 mining fields would be equal to 0.80 km^2. For example, the area of the internal dump and the mining pit of the Bełchatów Field operated by the Bełchatów Mine is currently about 32 km^2 [43]. It should be noted here that the Bełchatów Mine is the largest open-pit mine in Poland and one of the largest in Europe. This means, that it is possible to mine lignite in Poland using the HBM technology on a scale similar to current mining, with much lower mining costs and much less environmental degradation.

4. Conclusions

Lignite mining by open-pit methods requires many years of preparation (removal of significant amounts of overburden) and causes irreversible damage to the earth's surface. The use of the HBM method eliminates these problems.

The cost-effectiveness analysis of the preliminary concept of lignite mining using the HBM technology showed that it is market-competitive under the adopted calculation assumptions. The calculated cost of producing 1 Mg of lignite expressed by the DGC index is lower than the market prices of lignite from the period before the energy crisis in Europe caused by the outbreak of war in Ukraine, i.e., 2021 and January 2022. The calculated values of the NPV and IRR indicators also confirm that the HBM technology used for lignite mining can be economically effective.

The most important advantage of using the HBM technology for lignite mining in relation to open-pit mining is the shortening of the investment preparation process (mine construction) and a significant reduction in initial capital expenditure. In the case of open-pit mines, huge amounts of overburden must be removed before mining can begin. This is time-consuming (can take up to a decade) and very expensive.

The biggest impact on the cost of lignite mining using the HBM technology is the cost of purchasing backfill used to fill depleted caverns. They account for as much as 60% of the total mining costs. This means that if a cheaper backfill material is used (e.g., the accumulated overburden from depleted open-pit mines), it is possible to achieve a significant reduction in the cost of lignite production using the analyzed technology. However, changes in the market prices of lignite have the greatest impact on economic efficiency expressed in NPV and IRR indicators. Even a small decrease in market prices (by approximately 15.5% in relation to the adopted assumptions) makes the investment unprofitable.

The future potential of market opportunities of the HBM technology application in lignite mining is significant. At the current global level of lignite mining, it will be possible to exploit the available resources for another 400 years or so. In such a long timeframe, it will be possible to both refine and bring the HBM technology to utility on a commercial scale and then implement it widely.

It has been estimated that the simultaneous exploitation of 16 mining fields of 100×500 m each with the use of the HBM technology is sufficient to cover Poland's current demand for this resource. The total area of these 16 mining fields would be equal to 0.80 km^2, which is only 2.5% of the area of the internal dump and the mining pit of the Bełchatów Field, currently exploited by the Bełchatów Mine – the largest open-pit mine in Poland and one of the largest in Europe.

The application of the HBM technology to lignite mining still needs to be optimised and verified, in particularly including the following aspects:

- determination of the minimum distance between mining caverns,
- optimization of the mining process and transportation of excavated material to settling ponds,
- adaptation/preparation of the excavated material to the form of a market-ready product that can be used in industrial power generation.

Within the research works presented in the paper, these aspects were studied by numerical modelling, and laboratory or in-situ experiments up to a demonstration-scale lignite mining trial. Therefore, further research is still needed, including tests under various operational conditions, as well as the demonstration of the final version of the technology and the development of the market-ready version of the technology for wider commercialization and implementation.

The experiments and analyses performed so far with the results presented in the paper confirm the technical feasibility of mining lignite with the use of the HBM technology. Moreover, they indicate that it may be considered cost-competitive to the open-pit technology. When comparing the results of the cost analysis presented in this paper with the current purchase prices of lignite by professional thermal power plants in Poland, it should also be taken into account that the operating costs of the largest open-pit mines in Poland (Bełchatów, Turów) no longer include the costs associated with the construction of these mines, which were incurred several decades ago.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Duda A, Fidalgo Valverde G. Environmental and safety risks related to methane emissions in underground coal mine closure processes. Energies 2020;23:6312. https://doi.org/10.3390/en13236312.
[2] Fidalgo Valverde G, Duda A, Iglesias Rodríguez FJ, Frejowski A, Todorov I. Groundwater risk assessment in the context of an underground coal mine closure and an economic evaluation of proposed treatments: a case study. Energies 2021;14(6):1671. https://doi.org/10.3390/en14061671.
[3] Beck D. Applicability of hydraulic borehole mining ('HBHM') to diamondiferous deposits. Master thesis.. New Mexico, USA: New Mexico Institute of Mining and Technology, Department of Mineral Engineering Socorro; 2016. https://doi.org/10.13140/RG.2.2.14111.56485.
[4] Jura W. Attempt of adaptation of the method of hydro-openings in the coal deposits of strong methane threat and in "restricted" conditions (In Polish: próba adaptacji metody hydrootworowej w złożach węgla kamiennego o silnym zagrożeniu metanowym oraz w warunkach "skrępowanych"). Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie 2011;4:9−15. https://www.wug.gov.pl/wydawnictwa/archiwum/224/1686.
[5] Dibble MF. Borehole mining: improved technology expands horizon. Min Eng 1991;43(3):313−8.
[6] Kinley Exploration LCC. http://www.kinleyexploration.com/hydraulic-borehole-mining/.
[7] Takaya Y, Yasukawa K, Kawasaki T, Fujinaga K, Ohta J, Usui Y, et al. The tremendous potential of deepsea mud as a source of rare-earth elements. Sci Rep 2018;8:5763. https://doi:10.1038/s41598-018-23948-5.
[8] Maksymowicz M, Frejowski A, Bajcar A, Jura B. Application of hydro borehole mining (HBM) technology for lignite extraction- an environmental assessment (LCA) and a comparative study with the opencast method. Energies 2022;15:4845. https://doi.org/10.3390/en15134845.
[9] BAUER Group. https://www.bauer.de/export/shared/documents/pdf/bma/datenblatter/Mining_EN_905_852_2.pdf.
[10] Researchgate. https://www.researchgate.net/publication/296077919_Introducing_borehole_mining#fullTextFileContent11.
[11] Summers DA. Waterjetting technology. London: CRC Press; 2003.
[12] Savanick G. Borehole (slurry) mining of coal, uraniferous sandstone, oil sands, and phosphate ore. Bureau of Mines report of investigation RI 9101. Report of investigations (United States. Bureau of Mines 1987, 9101;1987, https://stacks.cdc.gov/view/cdc/10333/cdc_10333_DS1.pdf.
[13] Jura W. Hydraulic borehole mining (HBM) technology: an overview. In: Proceedings of the 19th world mining congress; Nov. 2003. p. 905−16. New Delhi, India; 1-5.
[14] Klich A, Jura W, Mazurkiewicz M. Application of water jet energy in the Borehole Mining. In: Proceedings of the 7th American water jet conference. USA: Seattle WA; August 1993. p. 473−84. 28-31.
[15] Dubiński J, Jura B, Makówka J, Janoszek T, Skiba J, Hildebandt R, et al. In-situ experimental study on hydro-borehole technology application to improve the hard coal excavating techniques in coal mine. Sci Rep 2023;13(1):1190. https://doi.org/10.1038/s41598-023-28501-7.
[16] Jura B, Jura W, Skiba J. Integrated extraction of coal and methane from the multi coal seams using hydro borehole mining technology. In: Proceedings of the 6th international symposium on green mining; November 2013. p. 24−6. Australia.
[17] Bondarchuk IB, Shenderova I. Classification of hydraulic borehole mining technological processes during pay zone development. IOP Conf Ser Earth Environ Sci 2015;24:012004. https://doi.org/10.1088/1755-1315/24/1/012004.
[18] Wen J, Chen C. Optimizing the structure of the straight cone nozzle and the parameters of borehole hydraulic mining for Huadian oil shale based on experimental research. Energies 2017;10(12):2021. https://doi.org/10.3390/en10122021.
[19] Xia B, Zeng X, Mao Z. Research on one borehole hydraulic coal mining system. Earth Sci Front 2008;15(4):222−6. https://doi.org/10.1016/S1872-5791(08)60057-3.
[20] Rochev V. Hydraulic borehole mining method possible application at Middle Larba alluvial gold field. E3S Web Conf 2018;56:01025. https://doi.org/10.1051/e3sconf/20185601025.
[21] Enany P, Shevchenko O, Drebenstedt C. Experimental evaluation of airlift performance for vertical pumping of water in underground mines. Mine Water Environ 2021;40(4):970−9. https://doi.org/10.1007/s10230-021-00807-w.
[22] Enany P, Shevchenko O, Drebenstedt C. Particle transport velocity in vertical transmission with an airlift pump. Fluid 2022;7(3):95. https://doi.org/10.3390/fluids7030095.
[23] Shimizu K, Takagi S. Study on the performance of a 200 m airlift pump for water and highly-viscous shear-thinning slurry. Int J Multiphas Flow 2021;142:1−12. https://doi.org/10.1016/j.ijmultiphaseflow.2021.103726.
[24] Ligus G, Zając D, Masiukiewicz M, Anweiler S. A new method of selecting the airlift pump optimum efficiency at low submergence ratios with the use of image analysis. Energies 2019;12(4):735. https://doi.org/10.3390/en12040735.
[25] Kujawiak S, Makowska M, Matz R. Hydraulic characteristics of the airlift pump. Acta Sci Pol Form 2018;4:85−95.
[26] Doyle RL, Halkyard JE. Large scale airlift experiments for application to deep ocean mining. In: Proceedings of ASME 2007 26th international conference on offshore mechanics and arctic engineering; June, 2007. p. 27−36. San Diego, California, USA; 10−15.
[27] Dubiński J, Szczepiński J, Bajcar A, Jura W, Skiba J, Jura B, et al. Assumption for the HydroCoal Plus project (in polish: założenia projektu HydroCoal Plus). Węgiel Brunatny 2018;4(105):44−6.
[28] Floyd EL, Chen J, Gordon P, Ireland S, Mabe B, Poon P, et al. Borehole hydraulic coal mining system analysis. Pasadena CA, USA: National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology; 1977.
[29] Central Mining Institute. https://hydrocoalplus.eu/.
[30] Burchart-Korol D, Krawczyk P, Czaplicka-Kolarz K, Smoliński A. Eco-efficiency of underground coal gasification (UCG) for electricity production. Fuel 2016;173:239−46.
[31] Krawczyk P, Śliwińska A. Eco-Efficiency assessment of the application of large-scale rechargeable batteries in a coal-fired power plant. Energies 2020;13(6):1384. https://doi.org/10.3390/en13061384.
[32] Rączka J. Cost effectiveness analysis based on dynamic generation cost index. Training materials developed under the TRANSFORM ADVICE PROGRAMME - investment in Environmental Infrastructure in Poland (In Polish: Analiza efektywności kosztowej w oparciu o wskaźnik dynamicznego

kosztu jednostkowego), https://view.officeapps.live.com/op/view.aspx?src=http%3A%2F%2Ftekstowa-edukacja.beta.nfosigw.gov.pl%2Fgfx%2Fnfosigw%2Fuserfiles%2Ffiles%2Fsrodki_zagraniczne%2Farchiwum%2Fispa%2Fprzygotowanie_przedsiewziec%2Fanaliza_dgc.doc&wdOrigin=BROWSELINK.
[33] Sierpińska M, Jachna T. Company assessment according to global standards. In: Polish: ocena przedsiębiorstwa według standardów światowych). Warsaw, Poland: PWN; 2000.
[34] Rogowski W. Investment effectiveness account. In: Polish: rachunek efektywności inwestycji). Warsaw, Poland: Wydawnictwo Nieoczywiste; 2018.
[35] European Commission EC. Guide to cost-benefit analysis of investment projects. Economic appraisal tool for cohesion policy 2014-2020. Brussels, Belgium EC. Directorate-General for Regional and Urban Policy; 2015.
[36] Ministry of Climate and Environment, MCE. Energy policy of Poland to 2040. Warsaw: Ministry of Climate and Environment; 2021.
[37] Ministry of Development, MDE. https://www.funduszeeuropejskie.gov.pl/media/95471/warianty_rozwoju_14_20.pdf.
[38] Pluta M, Wyrwa A, Zyśk J, Suwała W, Raczyński M. Scenario analysis of the development of the Polish power system towards achieving climate neutrality in 2050. Energies 2023;16:5918. https://doi.org/10.3390/en16165918.
[39] Druchin S, Klucznik M, Rybacki J, Sajnóg S, Sułkowski D. PIE economic review: summer 2023 (In Polish: przegląd gospodarczy PIE: lato 2023). Warsaw, Poland: Polish Economic Institute; 2023. https://pie.net.pl/wp-content/uploads/2023/08/Przeglad_gospodarczy_lato_2023.pdf.
[40] Krawczyk P, Howaniec N, Smoliński A. Economic efficiency analysis of substitute natural gas (SNG) production in steam gasification of coal with the utilization of HTR excess heat. Energy 2016;114:1207–13.
[41] Polish Energy Market Agency. Statistics of Polish power industry 2021 (In Polish: Statystyka elektroenergetyki polskiej 2021), https://www.are.waw.pl/badania-statystyczne/wynikowe-informacje-statystyczne/publikacje-roczne#statystyka-elektroenergetyki-polskiej.
[42] U.S. Energy Information Administration. https://www.eia.gov/energyexplained/coal/prices-and-outlook.php.
[43] PGE Górnictwo i Energetyka Konwencjonalna S.A., PGE. https://kwbbelchatow.pgegiek.pl/O-oddziale.
[44] Statista. https://www.statista.com/statistics/264779/countries-with-the-largest-soft-brown-coal-production/.
[45] Polish Geological Institute, PGI. https://geoportal.pgi.gov.pl/surowce/energetyczne/wegiel_brunatny.