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Application of Hydro Borehole Mining (HBM) Technology for Lignite Extraction—An Environmental Assessment (LCA) and a Comparative Study with the Opencast Method

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Abstract: The article presents the impact of lignite mining on the environment associated with the introduction of hydro borehole mining (HBM) technology. The results are partially based on the HydroCoal Plus project results, where an environmental assessment of lignite HBM technology was performed. In order to reach the goals of the task, a life cycle assessment (LCA) study was used to assess selected environmental aspects of the HBM single-borehole lignite production process covering selected environmental impact categories such as energy consumption, fuel consumption, water consumption and carbon footprint. The LCA procedure was adapted in an innovative way, constituting another added value to the shown research. The second part of this paper describes opportunities identified by the authors to minimize the environmental impact of lignite production by implementing the HBM method compared to the conventional opencast method.

Keywords: hydro borehole mining (HBM); life cycle assessment (LCA); environmental assessment; lignite mining

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1. Introduction

There is no doubt that the extraction and use of lignite bring devastating effects upon the natural environment on many levels. This natural resource, however, remains one of the dominant and most reliable sources of energy, playing an important role in meeting the world's energy needs [1–3]. Therefore, conducting research on the extraction of lignite in a manner that is potentially less harmful to the environment remains justified.

In addition to the traditional opencast methods of lignite extraction, there is the hydro borehole mining (HBM) method, which is not a universal method, but can be used in specific geological conditions [4–6]. The essence of the HBM method consists of drilling a production borehole, launching a multifunctional mining device (HBM tool) in the borehole, hydro-cutting of lignite deposit and hydro-crushing of the cut material as well as hydro-lifting the excavated material to surface using an "air-lift" system. The HBM method is widely described in the industry literature in terms of applied technological solutions [7–9]. Nevertheless, a few available environmental assessments of this method are limited to simple statements such as "environmental impacts are minimized" [10,11].

In this article, the authors aimed to present the results of an assessment of selected environmental aspects of the HBM lignite production process in a single borehole using the LCA (life cycle assessment) procedure [12,13]. The life cycle assessment (LCA) can be considered as a tool for a systemic assessment of environmental aspects concerning the life cycle of either a product or service; in addition, it can be adequate for assessing the

environmental aspects of processes. Depending upon the nature and intended purpose of an LCA study, the boundaries of the system under investigation may be altered, leading to a "cradle-to-gate" or "gate-to-gate" assessment, thus focusing on evaluating processes themselves. Therefore, it is an adequate method for use in HBM single borehole production process assessment. Although the method has been applied to several conventional coal-production-related environmental assessments, no LCA studies have been carried out for the HBM technology applied for the production of coal or lignite. The current assessment was performed as a part of the ongoing HydroCoal Plus project (a research project cofinanced by the Research Fund for Coal and Steel), aiming to better understand the HBM unit processes and its parameters in environmental terms. In addition to the LCA study performed, it was decided to extend the scope of the research for a second substantive part in which the environmental advantages of lignite extraction using the HBM method were presented in a descriptive manner and compared to the conventional lignite opencast mining method.

2. Materials and Methods

2.1. Choice of Methods for the Assessment

There are multiple tools and methods available for assessing the environmental performance of products, projects, systems or processes [14–20]. The life cycle assessment (LCA) study was chosen as the method for a major part of this research due to the fact of its flexibility [21]. The performed literature review suggests that the LCA method has never been used in a manner proposed by the authors of this report. According to [22,23], it is common for mining LCA studies to have a predefined set of data representing mining production systems. In the life cycles of products, mining systems are often represented as so called "black boxes", with predefined inputs and releases into the environment, without concerning the interpretation of the unit processes involved in the mineral extraction itself. On the other hand, LCA studies can be used for the environmental evaluation of processes. In this research, a process that is a part of an unconventional mining system was assessed. This can be considered an innovative approach to the application of LCAs, undoubtedly constituting another added value to the research. It should be emphasized that the conducted LCA study was based on appropriate standards [24–27]. In some parts of this article, the nomenclature defined in the abovementioned standards is used. Materials used for the data collection process included all the available information on HBM technology gained so far within the HydroCoal Plus project. Additionally, a survey was prepared in order to obtain the necessary data for the LCA study. The survey was completed by experts in the field of mining, geology, geomechanics and drilling. A group of 15 experts from GIG and the "Poltegor-Institute" supported by seven external experts in several brainstorming meetings based on their long experience in coal and lignite mining (underground and opencast) developed input data for the LCA analysis.

The scientific entity was represented by 68% of the experts and the mining and drilling industry/power hydraulic industry was represented by the other 32%. The range of years of experience in coal mining and drilling industry related activities was from 14 to over 40 years. The experts competence, calculated [28,29] as K_k (an indicator of an expert's competence defined as half the values of the coefficients: K_z—the factor determining the degree of knowledge held by the expert assessing the problem; K_a—coefficient of argumentation), was in the range 0.5–1.0 (Table 1).

Table 1. Summary of the experts' characteristics.

Years of Experience	Number of Experts from a Scientific Entity	Number of Experts from Industry
14–25	8	4
25–40	4	2
Over 40	3	1
Indicator of Experts' Competence	**Number of Experts from a Scientific Entity**	**Number of Experts from Industry**
0.5–0.6	2	1
0.7–0.8	8	4
0.9–1.0	5	2

During brainstorming meetings and meetings with experts, work options were defined for each of the HBM process components needed for the LCA as well as fuel consumption, energy consumption, water consumption, and emissions of noise and CO_2 into the atmosphere needed for the LCA analysis. After several meetings, taking into account the knowledge and experience of both GIG and "Poltegor-Institute" staff and external experts, a consensus was reached on both the details of the HBM process itself and the input data to be included in the LCA analysis. Brainstorming took place both in standing working groups and with invited external experts from the mining and drilling industry. This was a difficult and complex process given the innovative nature of the application of HBM technology in lignite mining and the small number of such experiments conducted worldwide.

The same approach was used for the purpose of the second substantive part of this research, which presents the environmental advantages of lignite extraction using HBM method compared to the opencast method.

2.2. Application of LCAs in Coal Mining Industry

The life cycle assessment (LCA) can be considered as a tool for a systemic assessment of environmental aspects concerning the life cycle of either a product or service; in addition, it can be adequate for assessing the environmental aspects of processes. An LCA study is a sufficient instrument to support environmental decisions [19,30]. An LCA study is a comprehensive method for quantifying and interpreting the environmental impacts of a product or service in a so called "cradle-to-grave" approach. However, depending on the nature and intended purpose of the LCA study, the boundaries of the system under investigation may be altered, leading to a "cradle-to-gate" or "gate-to-gate" assessment and, thus, focusing on evaluating the processes themselves. Basically, there are four phases included in a typical LCA study:

- The goal and scope definition phase (goal and scope definition);
- The inventory analysis phase (LCI);
- The impact assessment phase (LCIA);
- The interpretation phase (Interpretation) [31].

For coal or lignite, some LCA studies have been carried out in a "cradle-to-grave" approach, i.e., on the complete life cycle of the extracted material [22,23]. In this kind of approach, the whole mining process must considered as a "black box", with the energy produced from extracted material being considered as a final product. Only a few LCA studies have been conducted in a "cradle-to-gate" approach, focusing on mining processes specifically. These considered only conventional methods of mining (opencast mining, for instance). At the same time, no LCA studies have been carried out for the HBM technology applied for the production of coal or lignite.

2.3. Hydro Borehole Mining (HBM)

HBM, shown on the Figure 1, is a remotely operated (i.e., no underground personnel involved) in situ mining method of extracting rock material through boreholes using high-

pressure water jets. The technique of hydraulic mining integrates hydraulic fragmentation, jet pump lifting and air lifting. HBM employs at least four pipes: one for pumping down high-pressure water to feed water-jet cutting; a second for pumping the water to provide slurry transportation on the surface; a third to deliver compressed air for air-lift effect transportation; a fourth for slurry return [10,30]. The HBM method can be used in specific geological conditions. The essence of the method consists of drilling a production borehole, launching a multifunctional mining device in the borehole (HBM tool), the deposit hydro-cutting and hydro-crushing of the cut material as well as hydro-lifting of the excavated material to the surface via a modified "air-lift" system. It is assumed that after the completion of the mining process, the exploited cavern-shaped excavation (cavern) will be backfilled (with sand, for instance), the production borehole will be liquidated (with waste material, for instance), and the casing pipes will be recovered [32,33].

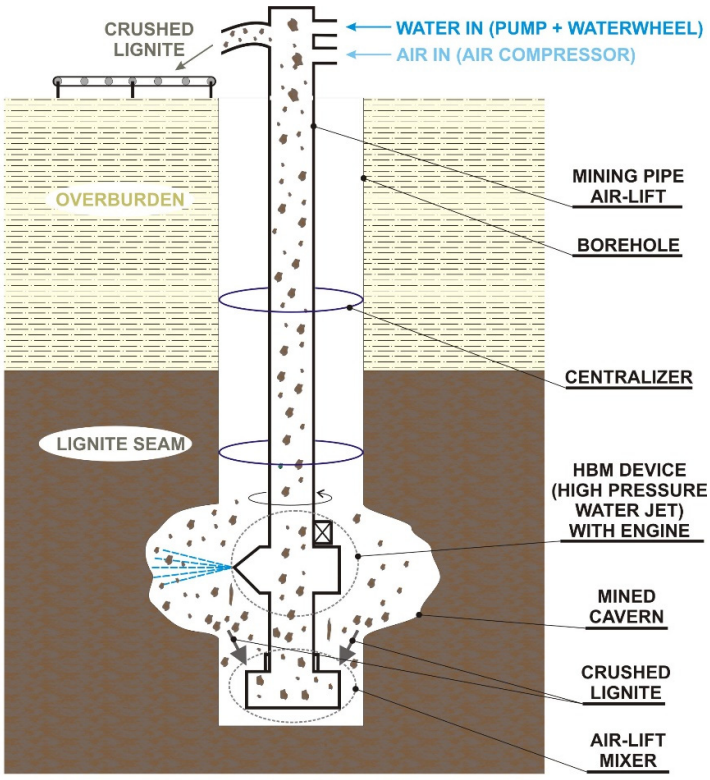


Figure 1. The concept of hydro borehole mining.

3. Results

This section presents both the results of the performed LCA study and the method by which they were obtained in line with the LCA procedure. Additionally, this section presents the results of the second substantive part of the performed research, where the environmental advantages of lignite extraction using the HBM method over conventional opencast mining method are presented.

3.1. Results of the Non-Site-Specific LCA of an HBM Lignite Production Process from a Single Borehole

3.1.1. Results of the Goal and Scope Definition Phase

This LCA study was carried out in accordance with the guidelines contained in standards [24–27]. The final goal of this LCA study, defined in accordance with the ISO 14040 standard, was to assess selected environmental aspects of lignite extraction using the HBM method from a single borehole. Moreover, another goal of this LCA study was to compare the formed lignite mining options of HBM technology usage, differentiated in terms of the amount of water and the amount of fuel used and, hence, differentiated in

terms of extraction process duration and efficiency. The conducted assessment aimed to illustrate the parameters of the mining process in quantitative terms, taking into account the environmental aspects. The authors assume that the conducted analysis will contribute to the general development of the HBM method of lignite extraction. The results of the analysis will contribute to a more complete understanding of HBM technology, also from an environmental perspective, by quantifying the parameters of the mining process.

The production system to be studied together with the system boundaries defined for the system are presented in the figure below (Figure 2).

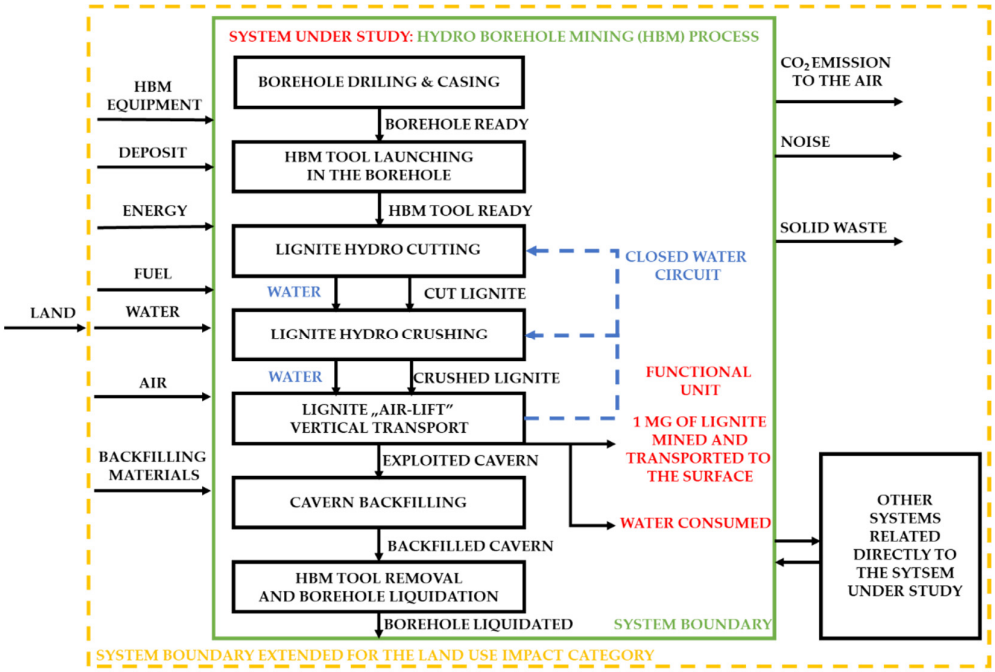


Figure 2. The system under an LCA study with its inputs, outputs, functional unit, and system boundaries included.

At this point, it should be emphasized that for the purpose of this LCA study, the investigated system was limited only to the technological activities included directly in the lignite hydro borehole mining (HBM) process. Other related processes or systems, such as deposit exploration, HBM tool production together with its transportation and liquidation, infrastructure construction and liquidation, mining and transportation of backfilling material, surface processes of lignite separation from water and lignite drying processes, among others, were omitted from the scope of this study. Some of the omitted processes and systems, however, were additionally included and used only for the purpose of the land use category impact assessment. Moreover, it was assumed that the water used for the lignite hydro-cutting and lignite hydro-crushing unit processes would be put into a closed circuit using a cooperating system. The assessment of this system was beyond the scope of this LCA study; however, the amounts of water used in HBM production take into account its interaction. Due to the existence of the water closed circuit, the amount of water used will be much smaller than the total amount of water actually consumed. Furthermore, it should be emphasized that the system defined for this study can be interpreted in two ways: either as a product system within which the lignite mined and transported to surface is treated as a product, using a "cradle-to-gate" approach (i.e., what happens next within the product life cycle is being omitted) or interpreted simply as a process, specifically, the process of lignite HBM production from a single borehole. While interpreting the defined system in any of these ways, the lignite mined and transported to the surface is treated as a product. Thus, the function of the investigated system has been defined as mining and transporting of lignite to the surface. Additionally, the backfilling of the created cavern and

liquidation of the production borehole are treated as additional functions of the system. Most importantly, 1 Mg (1 megagram) of lignite extracted and transported to the surface was assumed as the functional unit (the reference unit to which the inputs and outputs to the product system are related). This means that all data collected in the second phase of the LCA study, the LCI, will be then converted in relation to it (e.g., 4.01 kg of CO_2 emitted per 1 Mg of lignite mined and transported to surface).

In order to describe the defined system and be able to assess it in the most sufficient way, some assumptions had to be made. The main assumptions completing the basic necessary knowledge of the defined system are presented in the table below (Table 2).

Table 2. Assumptions made in order to describe the defined system sufficiently.

Parameter	Value	Unit
HBM production borehole depth	45	m
HBM production borehole diameter	550	mm
HBM production cavern target radius	4	m
Lignite seam depth interval	20–45	m
Unit weight of lignite	1.35	Mg/m^3

Some of the important information describing the defined system can be obtained from simple calculations based on the above assumptions, as presented in the table below (Table 3).

Table 3. Calculated complementary data on the defined system.

Data	Value	Unit
Material from drilling amount	10.7	m^3
Amount of solid waste from drilling	4.8	m^3
Amount of lignite from drilling	5.9	m^3
HBM production cavern target diameter	8.0	m
HBM production cavern target height	25.0	m
Lignite volume to be mined	1251.1	m^3
Lignite mass to be mined	1689.0	Mg
Total lignite volume (including the lignite from drilling)	1257.0	m^3
Total lignite mass (including the lignite from drilling)	1697.0	Mg

Based on the previous findings of the HydroCoal Plus project [34–37], it was assumed that the lignite HBM exploitation cavern would be cylindrical in shape, while its height would cover the total assumed lignite seam depth interval, i.e., it would be equal 25 m. Knowing the target radius of the production cavern, simple calculations allowed to obtain the lignite target volume and mass to be mined. However, these values increased by adding the amount of lignite obtained directly from the drilling process. Due to the technological solutions adapted to the hydro borehole mining technology, it was necessary to drill the production borehole down to the lignite seam bottom, from where the hydro borehole mining process commences [11]. Therefore, an insignificant amount of lignite (5.9 m^3) must be drilled through. Furthermore, within the main unit processes, the amount of lignite cut was assumed to be equal to the amount of lignite crushed and equal to the amount of lignite transported to surface via "air-lift" [35]. In other words, the amount of lignite was assumed to remain the same for all lignite-involved unit processes. Moreover, the unit processes of hydro-cutting and hydro-crushing were assumed to operate almost simultaneously, with similar process efficiencies.

For this non-site-specific assessment, the lignite deposit was assumed to be previously dewatered (via other system excluded from this LCA study). Moreover, the analyzed system cooperates with other system, which contributes to the amount of water to be used and consumed in a closed circuit. Taking into account that the water would be recovered

and put into a closed circuit, the actual water consumption would be equal to the water losses from a closed circuit. This was estimated based on the sum of the amounts of water escaping through the bottom and sides of the exploitation cavern during unit processes related to the use of water, and the amounts of water absorbed into the mined lignite. For the defined system, this amount was estimated as 2%, taking into account a general geological conditions of lignite deposition and lignite material characteristics. It was also assumed that the lignite seam was homogeneous, i.e., the material parameters were the same throughout the deposit and there were no inserts of other material in the lignite to be mined [38–40].

Moving forward, the impact categories selected for this LCA study were narrowed down only for the impact categories relevant for the previously defined goal of the study. The main criterion for choosing the impact categories was the availability of data in the second phase of the LCA study (LCI). The selected categories are as follow:

- Energy consumption;
- Fuel consumption;
- Water consumption;
- Carbon footprint;
- Land use;
- Solid waste generation;
- Abiotic resource depletion.

The chosen methodology for the life cycle impact assessment included a third phase in the LCA study, i.e., an LCIA to present the results of the second phase of the LCA study, the LCI, in relation to the functional unit of the system, assign it to the selected impact categories, and subsequently describe it [41,42].

In this LCA study, a number of different lignite HBM production options were compared. First, variants were differentiated within the lignite hydro-cutting unit process. There are two variants that differ from each other in terms of the amount of energy used and process parameters applied (i.e., amount of water and pressures used) and, hence, differ from each other in terms of extraction process duration and efficiency. Second, due to the estimated character of the data collection process, in some cases, data were given as ranges of values. Therefore, it was decided to refer to these values throughout differentiating it for two scenarios:

- Desired energy consumption scenario (minimum values from the data value ranges);
- Undesired energy consumption scenario (maximum values from the data value ranges).

Therefore, when considering that both lignite HBM production variants, differentiated within the hydro-cutting unit process, have a desired energy consumption and an undesired energy consumption scenario, four different options were compared in total (Figure 3):

- Option I—a desired energy consumption scenario for the first variant of process duration and efficiency;
- Option II—an undesired energy consumption scenario for the first variant of process duration and efficiency;
- Option III—a desired energy consumption scenario for the second variant of process duration and efficiency;
- Option IV—an undesired energy consumption scenario for the second variant of process duration and efficiency.

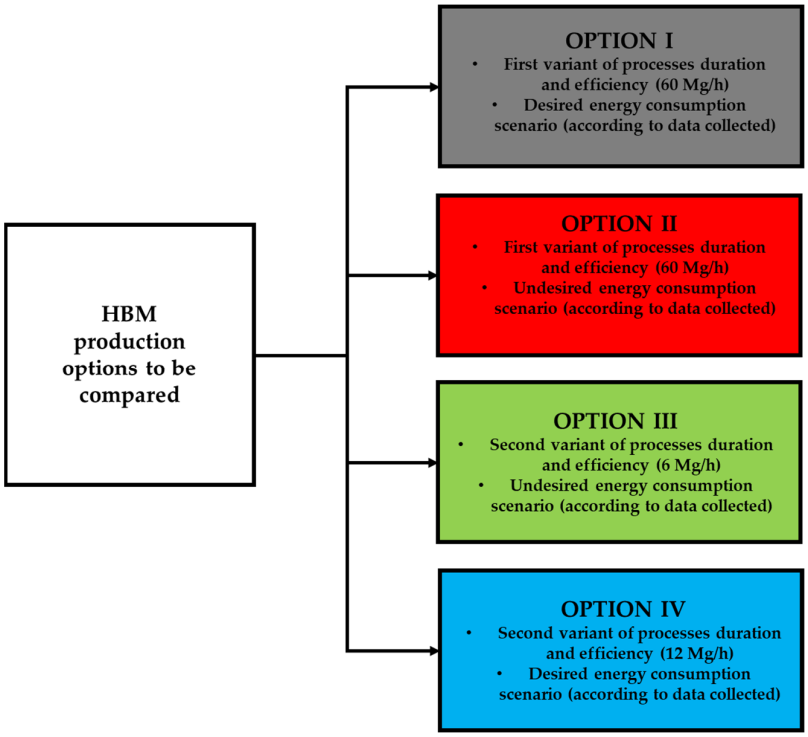


Figure 3. HBM lignite production options from a single borehole to be compared.

3.1.2. Results of the LCI (Life Cycle Inventory) Phase

In this phase of the LCA study, the data collection and calculation procedures were performed in order to quantify the relevant inputs and outputs for the previously defined production system. The process of data collection was very time consuming. In this study, a technology for lignite mining that has not been recognized from an environmental point of view so far was used. Therefore, the data could not have been measured or read from the industry literature; thus, all of the data were ultimately collected based on assumptions, estimates and calculations. The previously mentioned survey constituted one of the tools for data collection. Relatively greater or smaller attention was paid to the distinguished unit processes of the defined production system, according to the decided relevance of each of the unit processes in terms of meeting the requirements of the defined goal and scope of this study and according to the data's availability.

As an example, the details of the lignite hydro-cutting unit process are presented in the figure below (Figure 4), including the main inputs and outputs as well as the direct inputs from the environment and direct emissions into the environment.

The aggregate power was estimated to be in a range between 163 and 363 kW for different process efficiency variants. The lignite cutting efficiency for the first variant was estimated for 60 Mg/h, while the cutting efficiency for the second variant was estimated to be in a range between 6 and 12 Mg/h. Based on this, the total lignite cutting time in the cavern was calculated. It was equal to 28 h and 9 min for process efficiency variant I, and between 140 h 45 min (with 12 Mg/h process efficiency) and 281 h 30 min (with 6 Mg/h process efficiency) for variant II. Then, the total energy consumption for different options was possible to be calculated based on the aggregate power rating values and the estimated 70% power usage. Fuel (diesel) consumption data and noise emission data were estimated based on the experts' knowledge and experience. The CO_2 emissions data were estimated based on simple dependencies between diesel consumption and CO_2 emissions, allowing to calculate total CO_2 emissions from hydro-cutting process for all production options. The water pressures and water usage data (in a closed circuit) were assumed based on the knowledge gained so far within the HydroCoal Plus project. For both of the variants, the desired water pressure and water usage values were assigned to the desired

energy consumption scenario (smaller values of the data range), while the undesired water pressure and water usage values were assigned to the undesired energy consumption scenario analogically (greater values of the data range). Then, based on the assumed 2% total water loss from a closed circuit, the water consumption values were calculated. The land use remained neglected at this moment, taking into account that it was assessed for the whole defined system separately.

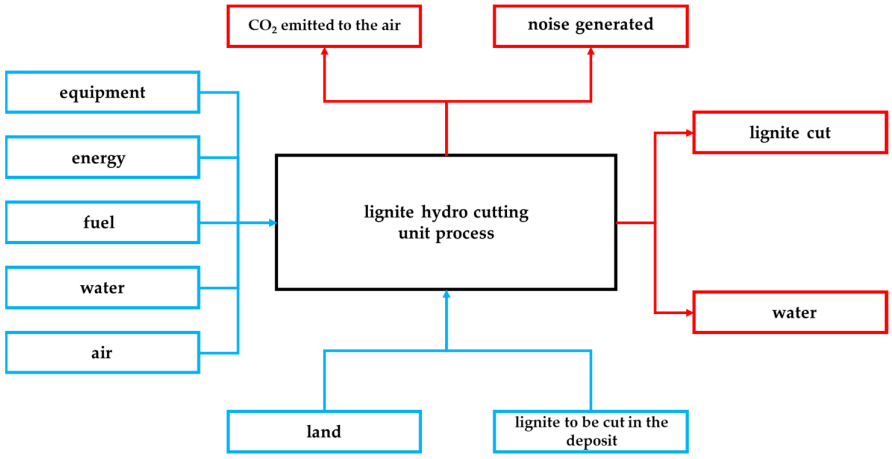


Figure 4. Details of the lignite hydro-cutting unit process (blue boxes—inputs, red boxes—outputs).

The results of the data collection for this unit process are presented in the figure below (Figure 5).

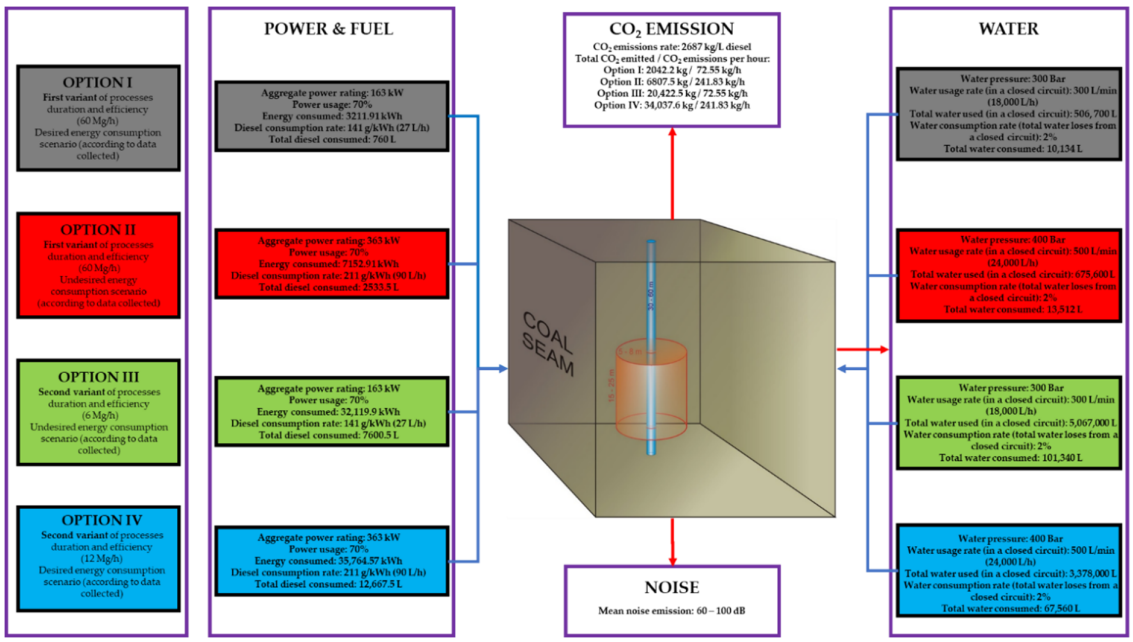


Figure 5. The results of the data collection for the lignite hydro-cutting unit process.

For all of the other unit processes defined in the system, the collected data were presented in a similar manner. All of the collected data allow to conclude that for the assessment of the HBM extraction process from a single borehole within impact categories, such as energy consumption, fuel consumption and carbon footprint, the following unit processes will be of key importance:

- Unit process of borehole drilling and casing;

- Unit process of lignite hydro-cutting;
- Unit process of lignite hydro-crushing.

For the impact category of water consumption, only the unit processes of lignite hydro-cutting and lignite hydro-crushing are of key importance. Based on the data collected, the four options of lignite HBM production to be compared were formed (Table 4). The further comparison of the production options concerned only the impact categories mentioned above. During the data collection, the rest of the unit processes of the system were decided to be of very low significance concerning the impact categories mentioned above.

Table 4. The characteristics of the four options of the HBM lignite production process.

Unit Process	Parameter	Unit	OPTION I	OPTION II	OPTION III	OPTION IV
			Values for Variant I—Desired Scenario	Values for Variant I—Undesired Scenario	Values for Variant II—Desired Scenario	Values for Variant II—Undesired Scenario
Borehole drilling and casing	Energy consumed	kWh	1260	1680	1260	1680
	Diesel consumed	L	300	400	300	400
	CO_2 emitted	kg	806	1075	806	1075
Lignite hydro cutting	Energy consumed	kWh	3212	7153	32,119	35,765
	Diesel consumed	L	760	2533	7600	12,667
	CO_2 emitted	kg	2042	6807	20,422	34,038
	Water consumed	L	10,134	13,512	101,340	67,560
Lignite hydro crushing	Energy consumed	kWh	2956	2956	29,557	14,779
	Diesel consumed	L	704	704	7037	3519
	CO_2 emitted	kg	1891	1891	18,910	9455
	Water consumed	L	2702	4053	27,024	20,268
Total	Energy consumed	kWh	7428	11,789	62,936	52,224
	Diesel consumed	L	1764	3637	14,937	16,586
	CO_2 emitted	kg	4739	9773	40,138	44,568
	Water consumed	L	12,836	17,565	128,364	87,828

Moving forward to the remaining impact categories, only the unit process of borehole drilling and casing can be indicated as one with importance for the solid waste generation impact category. Taking into account all the assumptions made within the scope of the study, the only solid waste resulting from the system's operation would be generated from drilling. The material generated from drilling would be 10.7 m^3 in total, including 4.8 m^3 of waste material (overburden) and 5.9 m^3 of lignite.

The abiotic resource depletion impact category concerns the whole defined system, and specifically, the main function of the defined system, which is mining and transporting of lignite to the surface. Moreover, this impact category can be addressed to the unit process of cavern backfilling, when treating the backfilling material as an abiotic resource as well. Due to the fact that lignite is being classified as an abiotic resource, the function of the defined system itself contributes to the abiotic resource depletion impact category. As it has been indicated, the total amount of lignite produced by the defined system was equal to 1697 Mg (1257 m^3).

As established during the goal and scope definition, the land use impact category was assessed separately for extended boundaries of the defined system (Figure 2). With regard to the land use impact category, it would be illogical to consider the HBM process itself (in such a case the land use would be minimal, i.e., equal to the cross-sectional area of the production borehole). Therefore, other systems cooperating with the defined system and the associated infrastructure around the production borehole were taken into account. According to [43], the area of land development for the purposes of HBM lignite extraction consists of the following elements (Figure 6):

- A borehole head;
- Pipe station (column modules and HBM tool head);
- Clean water tanks;
- Clean water filters for hydraulic aggregates (pumps);
- Settling tank;
- Pump station;

- Compressor station;
- Operator's cabin (container);
- Warehouse and workshop;
- Access roads and maneuvering area;
- Energy substation.

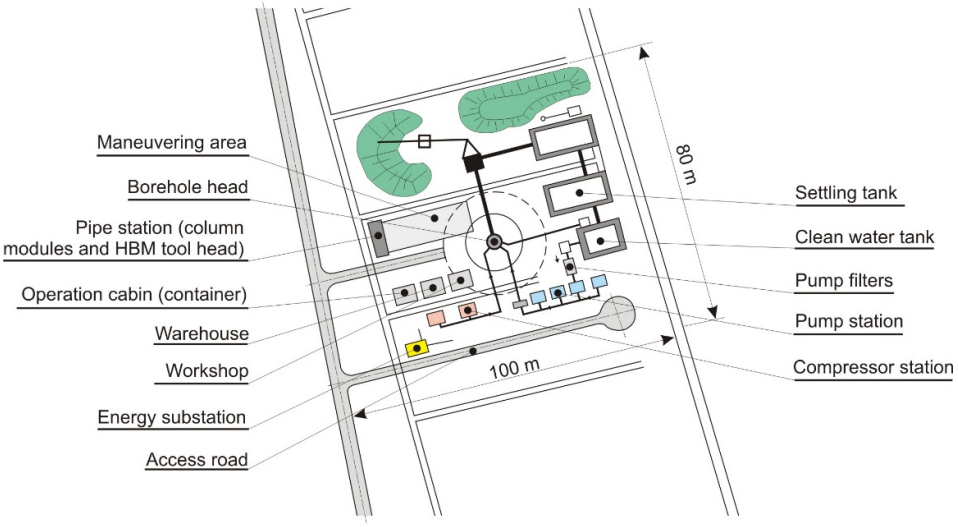


Figure 6. A site development plan around the HBM production borehole.

The required minimum area around the production borehole should be approximately 2000 m^2 (40 × 50 m), while the comfort area may have the dimensions of 80 × 100 m (8000 m^2) [43].

3.1.3. Results of the LCIA (Life Cycle Impact Assessment) Phase

In this phase of the performed LCA study, all of the selected impact categories were assessed. Where possible, the previous results were recalculated in relation to the functional unit of the defined system, which was 1 Mg of lignite mined and transported to the surface. Taking into account all the assumptions describing the defined system, the total amount of lignite mined and transported to the surface (including the lignite obtained from the drilling process) for each of the described mining options was equal to 1697 Mg. This value was used to recalculate the process parameters in relation to the functional unit. To simplify, the "1 Mg of lignite mined and transported to surface" will be hereinafter referred to as "1 Mg lignite".

The energy, fuel and water consumptions were assessed for three most relevant unit processes recognized, i.e., borehole drilling and casing; lignite hydro-cutting; lignite-hydro crushing. All previous results on the energy, fuel and water consumption and CO_2 emissions were recalculated in relation to the functional unit of the defined system (Table 5).

Table 5. Energy, fuel and water consumption and CO_2 emissions for the four options results.

Option	Unit Process	Energy Consumption		Fuel Consumption		CO_2 Emissions		Water Consumption	
		Value, kWh	Value, kWh/1 Mg Lignite	Value, L	Value, L/1 Mg Lignite	Value, kg	Value, kg/1 Mg Lignite	Value, L	Value, L/1 Mg Lignite
OPTION I	borehole drilling & casing	1260	0.74	300	0.18	806	0.47		
	lignite hydro cutting	3212	1.89	760	0.45	2042	1.20	10,134	5.97
	lignite hydro crushing	2956	1.74	704	0.41	1891	1.11	2702	1.59
	TOTAL FOR OPTION I	7428	4.38	1764	1.04	4739	2.79	12,836	7.56
OPTION II	borehole drilling & casing	1680	0.99	400	0.24	1075	0.63		
	lignite hydro cutting	7153	4.22	2533	1.49	6807	4.01	13,512	7.96
	lignite hydro crushing	2956	1.74	704	0.41	1891	1.11	4053	2.39
	TOTAL FOR OPTION II	11,789	6.95	3637	2.14	9773	5.76	17,565	10.35
OPTION III	borehole drilling & casing	1260	0.74	300	0.18	806	0.47		
	lignite hydro cutting	32,119	18.93	7600	4.48	20,422	12.03	101,340	59.72
	lignite hydro crushing	29,557	17.42	7037	4.15	18,910	11.14	27,024	15.92
	TOTAL FOR OPTION III	62,937	37.09	14,938	8.80	40,138	23.65	128,364	75.64
OPTION IV	borehole drilling & casing	1680	0.99	400	0.24	1075	0.63		
	lignite hydro cutting	35,765	21.08	12,667	7.46	34,038	20.06	67,560	39.81
	lignite hydro crushing	14,779	8.71	3519	2.07	9455	5.57	20,268	11.94
	TOTAL FOR OPTION IV	52,223	30.77	16,586	9.77	44,567	26.26	87,828	51.75

A comparison of the energy, fuel and water consumption for individual unit processes for different options is presented in figures below (Figure 7).

In addition, the values for the remaining selected impact categories, collected during the LCI phase, were recalculated at this stage in relation to the functional unit. This concerned the impact categories of solid waste generation and abiotic resource depletion. Taking into account all the assumptions made for the defined system, the obtained results are presented in the table below (Table 6).

Table 6. The results for solid waste generation and abiotic resource depletion impact categories.

Impact Category	Value	Unit
Solid waste generation	0.0028	m^3/L Mg lignite
Abiotic resource depletion	1	Mg/L Mg lignite

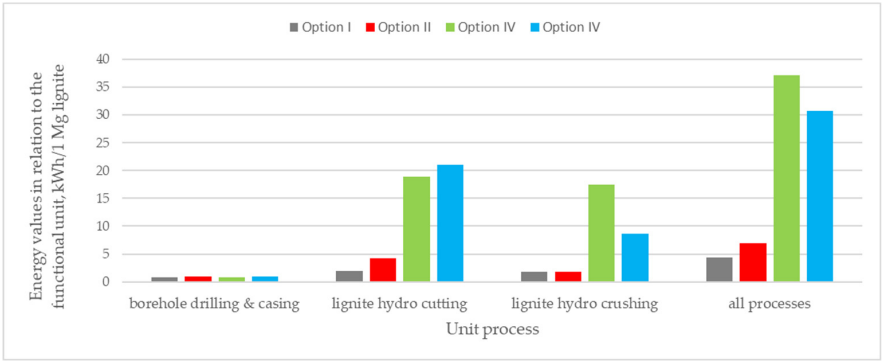
The only solid waste resulting from the system's operation would be generated from drilling (drilled through overburden), in the amount of 4.8 m^3 per 1697 Mg of lignite produced from a single cavern.

Due to the fact that lignite is being classified as an abiotic resource, the function of the defined system itself contributes to the abiotic resource depletion impact category. The total amount of lignite produced by the defined system was equal to 1697 Mg.

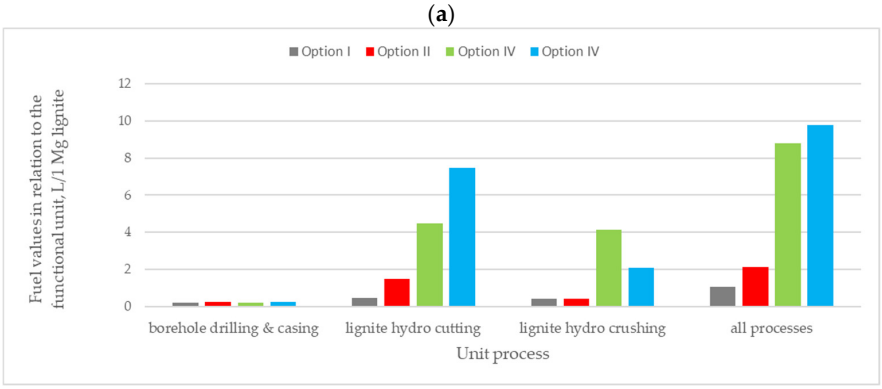
As it has been indicated during the scope definition, the land use impact category was assessed separately for an extended system. While treating the required minimum area and the comfort area around the production borehole as two scenarios (i.e., desired and undesired) in terms of the land use and recalculating the estimated areas in accordance with the reference unit, then:

- The land use would be equal to 1.179 m^2/1 Mg lignite (desired scenario);
- While the land use would be equal to 4.714 m^2/1 Mg lignite (undesired scenario).

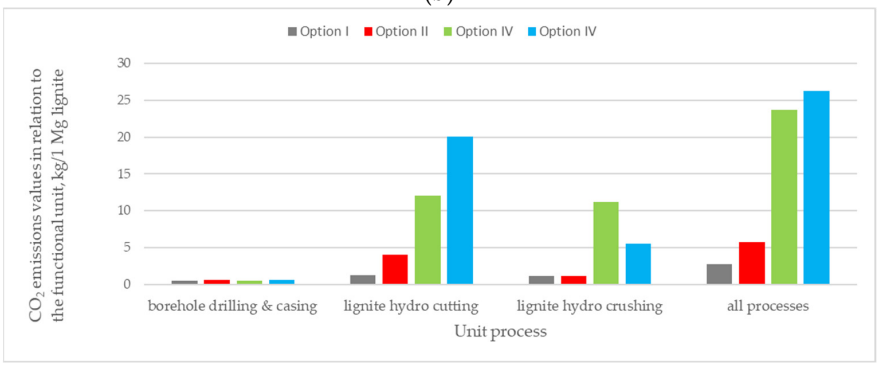
The interpretation of the results obtained in the LCIA phase is presented in the following.



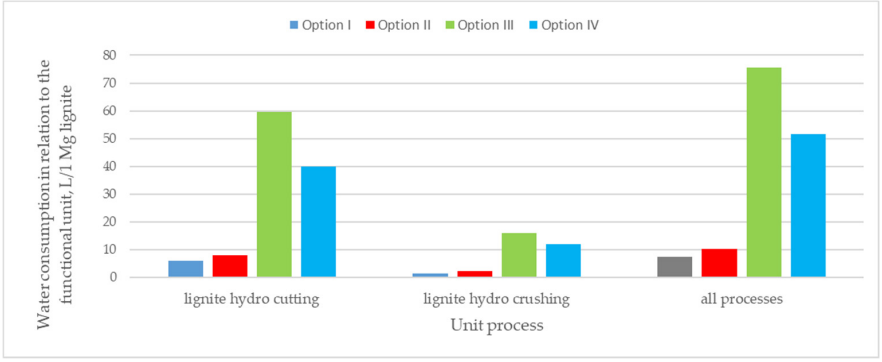
(**a**)



(**b**)



(**c**)



(**d**)

Figure 7. A comparison of unit processes energy consumption within different options and the total energy consumption for the system: (**a**) borehole drilling and casing unit process; (**b**) lignite hydro-cutting unit process; (**c**) lignite hydro-crushing unit process; (**d**) total energy consumption of the system for different options.

3.1.4. Key Insights of the Interpretation Phase

During the data collection phase, it was determined that the unit processes of borehole drilling and casing, lignite hydro-cutting and lignite hydro-crushing were the key processes for the environmental impact categories such as energy consumption, fuel consumption and carbon footprint. During the study, it was shown that the energy consumption differed for the four resulting mining options. Differences in energy consumption for individual variants resulted from the adopted different efficiencies of individual unit processes and associated different individual duration times. Additionally, the differences in energy consumption result from different aggregate power adopted for individual extraction options. The analysis showed that options I and II (energy consumption in relation to the functional unit equal to 4.38 and 6.95 kWh/1 Mg lignite, respectively) will be much less energy consuming than options III and IV (energy consumption in relation to the functional unit equal to 37.09 and 30.77 kWh/1 Mg lignite, respectively). In addition, the energy consumption of the individual unit processes will vary from option to option (Figure 7a). Each time (i.e., for all of the options) borehole drilling and casing turned out to be the least energy-consuming unit process among the processes identified as having a significant impact on energy consumption. Nevertheless, for HBM mining technology, the total energy consumption of the borehole drilling and casing process will depend directly on the depth of the lignite seam. As the depth of lignite deposition increased, the proportion of energy consumption by the drilling process in relation to other processes increased. Similar results were obtained for other impact categories such as fuel consumption and carbon footprint, which are directly related to energy consumption. Additional differentiation of the results resulted from the established ranges of fuel consumption for a unit process of lignite hydro-cutting. This range was set at 27–90 L/h, where the value equal to the lower limit of the range was assigned to the desired variants, and the value equal to the upper limit of the range was assigned to the undesirable variants. The analysis showed that options I and II (fuel consumption in relation to the functional unit equal to 1.04 and 2.14 L diesel/1 Mg lignite, respectively) consumed significantly less fuel than options III and IV (fuel consumption for the functional unit equal to 8.80 and 9.77 L diesel/1 Mg lignite, respectively). Moreover, similar to energy consumption, the fuel consumption by individual unit processes varied for each of the options (Figure 7b). Each time (i.e., for all options), among the processes identified as those significantly affecting fuel consumption, the least amount of fuel was used for the borehole drilling and casing unit process. CO_2 emissivity within individual unit processes and for individually defined production options resulted directly from fuel consumption, and the obtained results were directly proportional. The analysis showed that options I and II (CO_2 emissivity in relation to the functional unit equal to 2.79 and 5.76 kg CO_2/1 Mg lignite, respectively) were characterized by a significantly lower emissivity than options III and IV (emissivity CO_2 in relation to the functional unit equal to 23.65 and 26.26 kg CO_2/1 Mg lignite, respectively). Moreover, as for energy and fuel consumption, the CO_2 emissivity through individual unit processes varied for each option (Figure 7c). Each time (i.e., for all options), among the processes identified as those significantly affecting CO_2 emissions, the lowest CO_2 emissions were for the borehole drilling and casing unit process. Mining options I and II seemed to be the most likely ones. Lower energy consumption values, together with the resulting fuel consumption values and CO_2 emissions values, resulted primarily from the high efficiency of the process adopted for these options (60 Mg/h). However, the degree of recognition of the process did not allow for an unequivocal assumption of the efficiency of the process, which will depend on many parameters describing a specific lignite deposit to which a defined mining system can be adapted. Hence, in options III and IV, significantly lower values of the process efficiency were assigned (6–12 Mg/h).

For the water consumption category, unit processes such as lignite hydro-cutting and lignite hydro-crushing were examined, since only for these processes is water the supplied medium. The water consumption values resulted from the estimated water usage (in a closed circuit) and the assumed losses of the closed circuit of water. The other systems

whose functions will complement each other will cooperate with the defined system. It is assumed that much of the water in use within the operation of the studied system can be recovered through the other system of lignite separation from the water, and then reused in the unit processes of the system analyzed in this LCA study. Thus, water could be treated both as an input into the system and an output from the system (as a coproduct) that is being fed into a closed circuit (Figure 2). The variation in the total water consumption resulted from different values of water usage estimated for individual unit processes for the different options as well as different duration times of the individual options, which resulted from the efficiency of the processes. It was found that for each of the four production options, the water consumption of the lignite hydro cutting process will be significantly greater (three to four times greater) than the water consumption of the lignite hydro crushing process. The total water consumption for the various options will be much lower for options I and II than for options III and IV. This is mainly due to the much lower efficiency of the unit processes for options III and IV, and the longer duration of the processes associated with it (Figure 7d). For the lignite "air-lift" vertical transport unit process, it was assumed that the amount of water supplied to the system during the two abovementioned processes would be sufficient. Moreover, the authors of this article see an opportunity to use water from the complementary drainage processes (other system) of a hypothetical lignite deposit and put this water into the aforementioned closed circuit.

3.2. Results of an Additional Comparative Study of HBM and Opencast Lignite Mining

During the implementation of the previously presented LCA study, it was decided by the authors to add a complementary part dedicated to lignite opencast mining. Occasionally, references to individual findings obtained during the LCA study will be made in this part.

It is often outlined in the industry literature [18,19] that in contrast to the LCA study performed by the authors, environmental assessments of mining and mining-related activities should be site specific. A complex analysis could only be conducted for a site-specific mining project created for the development of a specific deposit. Nevertheless, while assessing a process (HBM lignite production) in the early stage of its development, it does not deal with a specific mining project but with an assessment of an unconventional mining technology itself. Taking into account that it is impossible to quantify many environmental impacts for a non-site-specific assessment, it was decided to conduct a simple analysis involving a comparison of the lignite HBM method with a conventional lignite opencast mining method. Throughout the selected categories of environmental impacts indicated below, the environmental advantages and the chances of minimizing the environmental impacts expected when implementing the HBM method of lignite extraction instead of conventional methods are emphasized.

3.2.1. Land Use

Both opencast mining and HBM use a portion of land in order to conduct mining operations. The land use in the opencast mining is tremendously large for a very long time. It is associated with a processes of opening a lignite deposit out which involves removing large amounts of overburden material. The land is being used for relatively long time, taking into account that the reclamation activities start after several or even more years of the mine's operation. Moreover, sometimes the terrain is irreversibly transformed (depending on the chosen method of reclamation). On the other hand, the use of the HBM method of lignite extraction brings potential chances to minimize the land use factor:

- First, there is no need to remove the overburden, which is a very time-consuming activity; thus, the land is used for a much shorter period of time;
- Secondly, without the overburden removal, there is no need to create any external dumps, which are associated with using of another portion of land;
- Third, the mining area is left almost intact after the extraction ends unlike the opencast method.

It must be emphasized that the lignite HBM technology obviously requires the infrastructure to be built for all of the processes necessary to extract and transport the lignite together with the infrastructure for all the auxiliary processes. Although the land use for the HBM technology has been recognized only in terms of the land being used for a single-borehole lignite production, it is certainly expected to be minimized comparing to the opencast lignite mining. A mine-scale mining project of lignite production with the use of HBM technology will undoubtedly not involve the building of a totally separate infrastructure for every single borehole but will look for optimal solutions of combining some of the infrastructure for more production boreholes or for solutions such as using of mobile equipment and infrastructure. This will be one of the topics investigated during the next stages of the ongoing HydroCoal Plus project.

The duration of all single unit processes within HBM technology will depend on many factors such as deposit depth and production cavern dimensions. Nevertheless, the total duration of the activities related to lignite extraction from a single cavern, cavern backfilling and borehole liquidation can be estimated to vary between a couple of days and several weeks. After performing the abovementioned activities and relocating the infrastructure, the used area returns to a state similar to the one before the extraction.

To summarize, less land is expected to be used by the HBM mining method than by the traditional opencast mining method. Moreover, the land will be used for a much shorter period of time, being incomparably less transformed.

3.2.2. Solid Waste

Both opencast mining and HBM generates a solid waste. However, the difference in the amount of solid waste generated by these methods is huge. The large amounts of solid waste generated during the lignite mining with the opencast method is mainly due to the overburden removal process. The removed overburden material constitutes a waste, at least temporarily, until it is used within reclamation procedures or otherwise used. Taking into account, that the depths of deposition and thicknesses of Polish lignite deposits result in the values of stripping ratios reaching up to 10:1 [44], the amount of overburden material that is necessary to be removed in order to open a lignite deposit out may be over 10 times greater than the volume of lignite to be mined. Contrary to the opencast method, HBM technology does not require overburden removal. The deposit is reached by a drilling process that generates minimum amounts of solid waste in comparison to overburden removal. A conducted LCA study for the process of single-borehole lignite production indicated that for a 45 m deep production borehole 550 mm in diameter and a production cavern with a 4 m radius and 25 m in height, the amount of solid waste generated would only be approximately 0.0028 m^3 per 1 Mg of lignite produced. Moreover, for the production of lignite using the HBM method, it will be possible in some cases to use the solid waste generated from drilling for partial backfilling of the exploitation cavern or liquidation of the borehole.

3.2.3. Energy Use

This category is difficult assess for a non-site-specific assessment. The energy use both for lignite mining and lignite HBM production is dependent on site-specific conditions of lignite seam deposition. However, taking into account the previously mentioned overburden removal need within the opencast mining method, and the tremendous amounts of energy being consumed in order to do so, the authors of this report tend to say that the total energy required to extract lignite with the HBM method will be much smaller than the total energy required for the opencast lignite extraction. Moreover, in opencast mining, the obligatory reclamation works require additional energy expenditure, while in mining with the HBM method, reclamation of the post-mining area will be much less energy consuming. Nevertheless, the issue of energy consumption in the process of lignite mining using the HBM method is not yet sufficiently researched to be able to make comparative statements based on specific values.

3.2.4. Fuel Use

Fuel use in the case of HBM production is strongly related to energy use, since the energy is planned to be supplied from the use of power generators powered by diesel. However, there is a chance to eliminate this need by using the energy directly from a power grid. The possibility to adapt this solution should be investigated in relation to a site-specific mining project. The authors of this article suggest that this should be considered during the next stages of the HydroCoal Plus project. The HBM production process, in general, is predicted to use less fuel than conventional opencast mining. This is due to the fact that there is no need of overburden removal within HBM lignite production, which usually contributes to a major part of the energy usage and, hence, the fuel usage. There is many more machines and vehicles powered on fuel necessary for the opencast methods of mining than for the HBM method.

3.2.5. Water Use and Water Consumption

Water use is an environmental category where the lignite HBM method loses in comparison with the opencast lignite mining method [45–47]. This is due to the fact that during the HBM production, water constitutes a medium that is used directly for processes such as lignite cutting, lignite crushing and transporting the lignite to a surface. However, during the implementation of this task, the authors of this report noticed a chance to minimize water consumption by putting the water used in an HBM process into a closed circuit. According to the LCA study conducted, the eventual water consumption was estimated to be equal the losses of water from the closed circuit mentioned above. This would be equal the losses of water via production cavern bottom and sides and via soaking the water into the lignite mined. This value was generally estimated to be approximately 2%, taking into account the general geological conditions of lignite deposition and lignite material characteristics. Nevertheless, this will be strongly dependent on a site-specific conditions. It is recommended to include the system of a closed water circuit during the next stages of the HydroCoal Plus project.

3.2.6. Emissions to Air

The emissions into the air, such as GHG emissions, are associated with the use of fuels in the processes of mining [48]. As indicated before, the HBM lignite mining is predicted to utilize less fuel than the lignite mining with conventional methods. Moreover, the activities within opencast mining of lignite release dust particulates and various gaseous pollutants resulting from the fact that a deposit is being opened out to a surface after the overburden is removed. These kind of impacts are zeroed with the use of the lignite HBM method.

3.2.7. Water Quality

Mining activities undoubtedly influence water quality [49,50]. The major danger for lignite mining is the formation of so-called acid mine drainage (AMD). AMD is created via the oxidation of sulphide minerals (such as pyrite, for instance) in the presence of water. This results in effluent that is acidic and rich in metals and sulphate ions. This phenomenon is caused directly by the deposit dewatering processes. Deposit dewatering is obviously necessary for the purposes of lignite opencast mining. On the other hand, for the lignite HBM technology, some authors and researchers suggests that there is no need to dewater the deposit. However, the findings of the HydroCoal Plus project currently obtained showed that the process of lignite hydro cutting will be ineffective in water conditions. Therefore, the deposit dewatering that creates the possibility of causing AMD is necessary. However, the intensity of AMD formation is time dependent. It is expected that HBM lignite mining activities last much less longer than the lignite opencast mining activities; hence, the time of the deposit being dewatered is minimized. Moreover, the HBM technology itself brings many opportunities to prevent AMD risk. For instance, the backfilling material could constitute carbonate minerals that neutralize AMD's potential.

4. Discussion

The conducted LCA study on selected environmental impacts of lignite single-borehole HBM production contributed to a better understanding of the unit processes within HBM technology by quantifying and presenting the process parameters in relation to 1 Mg of lignite mined and transported to surface. Borehole drilling and casing, lignite hydro-cutting and lignite hydro-crushing unit processes have been identified as crucial unit processes of HBM production, also in environmental performance terms.

From the options formed during the LCA study conduction, option I and option II have were as those reflecting reality in the most reliable way. The authors of this article put emphasis on testing and measuring the lignite HBM production process parameters during any planned field tests, also in accordance with the environmental performance.

For all of the HBM production options, lignite hydro-cutting and lignite hydro-crushing turned out to be the most energy consuming. Nevertheless, for the HBM mining technology, the total energy consumption of the borehole drilling and casing process may be greater, since it depends directly on the depth of the lignite seam deposition.

The crucial unit processes of HBM production utilize water. In order to minimize the water consumption of the HBM production, the water must be put into a closed circuit.

The conducted LCA study showed that the environmental impacts of HBM production on categories such as land use and solid waste generation were minimal. This was mainly due to the fact that there was no need for opening the deposit by removing the overburden, while all the process related to HBM mining last for a relatively short period.

In the second complementary part of this article, the advantages of the lignite HBM method over conventional opencast method were shown. The implementation of HBM technology brings chances to minimize environmental impacts of lignite extraction on many levels, especially within impact categories such as land use and solid waste generation.

The authors suggest that an appropriate mining project on the scale of an entire mine and technological solutions applied for the needs of cooperation between different systems should be similarly assessed; thus, it will significantly affect the environmental aspect of lignite production via HBM.

5. Conclusions

This research led to many valuable insights such as:

- The borehole drilling and casing, lignite hydro-cutting and lignite hydro-crushing unit processes were the most significant processes for HBM lignite production systems in terms of environmental performance;
- The HBM technology brings many opportunities to minimize the environmental impacts of lignite extraction in many areas, especially for the land use and solid waste generation impact categories, as it was compared in the second part of this article;
- The LCA procedure can be used in a less conventional way in order to assess processes; assess only the raw material acquisition stage of life cycles of products; even to assess processes within the raw material acquisition stage, as shown is this study;
- Any environmental assessment of mining processes and systems should be (where possible) site specific; in a non-site-specific environmental assessment, as in this case, many assumptions are required, and generalization of several issues may be inevitable.

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