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Achieving climate neutrality in coal mining regions through the underground coal gasification

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Abstract. Coal mining regions face significant challenges in transitioning towards climate neutrality due to their dependence on fossil fuel extraction. This research explores the potential of underground coal gasification (UCG) technology as a pathway towards climate neutrality in these regions. UCG involves converting coal in-situ into syngas, a cleaner-burning fuel, while mitigating greenhouse gas emissions. The study investigates the material-thermal parameters of the gasification process using the MTB SPGV software and analyzes the gas concentration and producer gas yield parameters in the "Stepova" Mine field of SE "Lvivvuhillia". Additionally, technological solutions for achieving climate neutrality through carbon dioxide (CO_2) utilization are proposed, focusing on pre-separation of CO_2 from producer gas obtained during UCG. A technological scheme for CO_2 utilization is presented, outlining the steps from gas extraction to storage and utilization in underground spaces. The proposed method offers a promising approach to mitigate CO_2 emissions and optimize resource utilization in coal-mining regions, contributing to global efforts for environmental sustainability and climate action.

1 Introduction

The issue of global warming is one of the most important issues for modern society. That is why the world is making extensive efforts to reduce greenhouse gas emissions in the industrial sector and other sectors of the economy. A key direction is the transition to the use of renewable energy sources, which includes active development of solar, wind and hydropower, as well as other sources that are not based on the use of hydrocarbons [1 – 5]. Energy-efficient technologies implemented in production and consumption play a significant role in reducing emissions [6, 7].

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Other measures may include regulating greenhouse gas emissions at the legislative level, introducing emission offset programmes (quota systems), and encouraging research and development of clean technologies. Such activities are used both at the international and national levels with the aim of reducing the impact of anthropogenic factors on climate change and the environmental sustainability of the planet [8 – 10].

Currently, most of the world's signatories to the Paris Agreement have set their climate goals and commitments to reduce greenhouse gas emissions at the international level [11]. Alongside this, more than 30 states have publicly committed to achieving carbon neutrality, that is, balancing emissions and absorption [12 – 14].

As outlined in the Paris Agreement, there is a mandate to decrease global coal production capacity by 80%. Despite this, renewable energy sources have not yet reached a level of sustainability to fully meet energy demands. Consequently, there remains a significant reliance on coal energy to maintain a stable energy supply [15 – 17]. Addressing the challenges of post-war reconstruction in Ukraine, research [18] suggests that achieving energy independence and aligning with the principles of the Green Deal could potentially require investments more than one hundred billion dollars for the country. But this value can be even higher when considering mass attacks on Ukraine's energy infrastructure during since 2022 up to date [19].

Ukraine has committed itself to implementing a climate-neutral course for the energy sector [20, 21]. Measures to save energy, improve energy efficiency, and reduce greenhouse gas emissions are being implemented. Projects in the renewable energy sector are being implemented and fossil fuels are being phased out, particularly with regard to coal mining and consumption [22, 23]. About 80% of greenhouse gas emissions are related to the extraction, transportation, and consumption of energy resources, including fossil fuels. The share of the industrial sector in the structure of global greenhouse gas emissions is about 6%; in Ukraine, this figure reaches 18% [24].

In the context of global decarbonization, projects aimed at reducing the use of hydrocarbon energy are important [25 – 27]. In the current realities of the country's fuel and energy complex, this is an impossible task. It is therefore necessary to partially find ways to address this problem, ways to help gradually reduce dependence on hydrocarbon energy [28].

Ukraine has significant coal potential, ranking first in Europe and eighth in the world in terms of coal reserves, estimated at 120 billion tons. The diversity of on-balance coal reserves includes both low-grade coal and highly metamorphosed anthracites [29 – 31]. The main hard coal reserves are concentrated in the Donetsk and Lviv-Volyn coal basins. Military conflicts in the east of the country since 2014 and the war in 2022 have exacerbated the negative consequences of the restructuring of the coal industry [32]. Therefore, the tasks of developing and implementing alternative technologies for coal mining and processing in a closed ecological cycle are very relevant today. At the same time, the overall development of coal-mining regions should be based on the implementation of effective technological, environmental, social and economic solutions in compliance with the principles of climate neutrality. To achieve this, a number of measures and strategies need to be developed and implemented based on:

– transition to renewable energy sources by developing renewable energy sources such as solar, wind and hydropower;

– introducing energy efficiency programs and technologies that reduce energy consumption and carbon emissions;

– restoration of natural ecosystems and rehabilitation of territories disturbed by coal mining enterprises;

– social development and labour force requalification by providing alternative employment opportunities for local people who have lost their jobs due to the closure of coal mining enterprises or the phasing out of mining operations;

– funding research and innovation in the field of clean energy and green technologies.

An important basis for achieving climate neutrality in coal-mining regions is also a partnership between the government, the public and the private sector to jointly implement these strategies [33]. After all, it is only through joint efforts that significant results can be achieved in reducing the climate and environmental impact of the coal industry [34 – 36].

In accordance with the Concept of the State target program for the Fair transformation of coal regions of Ukraine for the period until 2030 (Resolution of the CMU dated September 22, 2021 No. 1024 "On approval of the Concept of the State target program for the Fair Transformation of the Coal Regions of Ukraine for the Period until 2030"), the following problems require urgent solution:

– low level of investment attractiveness caused by unprofitability of state-owned enterprises in the coal industry;

– the monocultural nature of the local economy in coal-mining regions; ineffective government social policy in coal-mining regions;

– low level of social and critical infrastructure development in settlements of coal-mining regions;

– environmental degradation due to the operation and/or closure of coal enterprises;

– social tension among the population of the territories where coal enterprises are located, which are in the process of liquidation, conservation or reorientation to other types of economic activity.

Today, a number of the first pilot projects are being considered regarding the creation of tourist and technological centers on the basis of coal enterprises: "Velykomostivska" Mine (the city of Chervonohrad, Lviv Oblast), 5/6 Mine (the city of Myrnohrad, until 2016 – Dymytrov, Donetsk Oblast) [37]. This approach is quite valid when coal reserves are depleted [38]. However, given the existing potential, it is necessary, first of all, to consider the possibility of implementing innovative technological solutions for coal mining.

Underground gasification geotechnology can become an essential element in the transition to a more sustainable use of coal in an environmentally friendly cycle. In Ukraine, over 40.1 billion tons of coal seam reserves are suitable for underground gasification, which is over 30% of the total volumes (117 billion tons). Currently, about 20 billion tons of on-balance and 3.8 billion tons of off-balance hard coal reserves, as well as 1.1 billion tons of on-balance and 0.2 billion tons of off-balance brown coal reserves, can be used for underground gasification [39 – 41].

Underground coal gasification is a complex physical-chemical process consisting of a series of continuous phases. The gasification process occurs at the gas-solid interface. Coal gasification is based on either incomplete fuel combustion (with a lack of oxygen) or complete fuel combustion followed by the reaction of carbon with carbon dioxide and water vapor to generate combustible producer gases (CO, H_2, CH_4) [42]. The essence of underground coal gasification technology is as follows (Fig. 1).

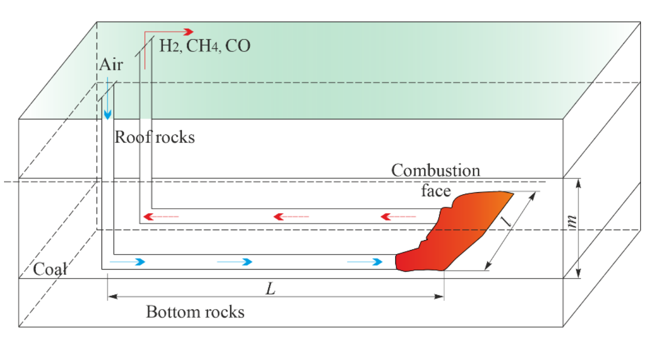

Fig. 1. Technological scheme of underground coal gasification process: *m* – coal seam thickness, m; l – combustion face length, m; *L* – gasification column length, m.

Two wells are drilled from the earth's surface to the intersection with the coal seam: the blast injection well and the gas-outlet well. The horizontal part of the wells is drilled through the coal seam. After that, a reaction channel is formed between the wells using one of the well-known methods of directional drilling, hydraulic or pneumatic fracturing, etc. A blast mixture, which is represented by air, oxygen-enriched air or a steam-air mixture is supplied into one of the wells. And through another well, producer gas is removed [43].

The coal gasification process occurs between the specified wells with the formation of reaction zones of an underground gasifier, which are characterized by variable temperature field parameters [44]. In this case, the composition of the producer gas of the coal gasification process is determined not only by the solid fuel elemental composition and the type of blast supplied to the underground gasifier, but also by the ratio between the lengths of the oxidative/reduction zones and the average temperature of the gas phase within each of these zones [45].

In the oxidative zone of the underground gasifier, combustion of carbon and oxygen occurs, which are in the blast mixture supplied to the underground gasifier by primary reactions (q – thermal energy, generated during the reaction process) [46]:

$$C + O_2 = CO_2 + q; \quad (1)$$

$$2C + O_2 = 2CO + q; \quad (2)$$

$$C + H_2O = CO + H_2 + q; \quad (3)$$

$$C + 2H_2O = CO_2 + 2H_2 - q. \quad (4)$$

Gaseous products formed as a result of primary reactions react with fuel carbon, oxygen, water vapor and with each other:

$$C + CO_2 = 2CO_2 \pm q; \quad (5)$$

$$C + 2H_2 = CH_4 \pm q; \quad (6)$$

$$2CO + O_2 = 2CO_2 + q; \quad (7)$$

$$2H_2 + O_2 = 2H_2O + q; \quad (8)$$

$$CH_4 + 2O_2 = CO_2 + 2H_2O + q; \quad (9)$$

$$CO + H_2O = CO_2 + H_2 \pm q; \quad (10)$$

$$2CO + 2H_2 = CH_4 + CO_2 \pm q; \quad (11)$$

$$CO + 3H_2 = CH_4 + H_2O + q. \quad (12)$$

Reactions (1) and (2) are the main sources of heat, which is consumed when carbon interacts with water vapor (3) and (4). Consequently, at elevated temperatures, an increase in the yield of products formed by reactions (3), (6), (10), (11) can be expected. Controlled temperature increase promotes intensification of chemical reactions [46], which leads to a more efficient conversion of coal into combustible and ballast gases. High temperature stimulates the cleavage of carbon bonds and improves the gasification level. In this way number of intensification methods can be applied [47 – 49].

Carbon dioxide is a by-product of underground gasification, and as it is considered a greenhouse gas, its emissions can be hazardous to the environment. However, there are a variety of carbon capture and storage (CCS) technologies available to reduce the carbon dioxide emissions into the atmosphere [50, 51]. In addition, carbon dioxide can be used in various industrial processes, such as the production of synthetic fuels, carbonaceous materials or in agriculture as plant fertilizer. Carbon dioxide produced from coal gasification can be a valuable resource that is used to create a sustainable and economically viable coal gasification process. Therefore, in the context of climate neutrality of coal-mining regions and in the conditions of their safe transformation based on underground gasification technology, it is necessary, first of all, to assess the potential of this technology by taking into account the qualitative-elemental composition of coal and the qualitative-quantitative initial mixture (producer gas). This technology can become the basis of decarbonization of many national and global climate change programs through modern carbon capture and storage technologies in technogenically formed georeactor systems.

Thus, the purpose of this research is to determine the dependence of change in the yield of producer gases depending on the concentration activity of carbon dioxide in the blast mixture to achieve climate neutrality in coal-mining regions based on the underground coal gasification technology. To achieve this purpose, the authors set and solve the following scientific and practical tasks:

– to analyze the mining-geological conditions of the occurrence of coal seams in the conditions of the "Stepova" Mine, SE "Lvivvuhillia";

– using computer modeling, predict the yield parameters of producer gases from coal gasification;

– to study the parameters of carbon dioxide influence on the gasification process efficiency;

– propose technological solutions for carbon dioxide utilization in technogenically formed georeactor systems.

2 Research methods

The producer gas yield parameters depending on the coal grade composition are assessed by studying the material-thermal parameters of the process. For this purpose, the authors of the research use the MTB SPGV software product. The initial data on coal suitable for gasification (chemical and technical composition) and technological parameters of the process (combustion face length, coal seam thickness, type of blast mixture, water inrush) are entered into the program calculation algorithm [52, 53].

The Stepova Mine field of the SE Lvivvuhillya (Lviv-Volyn coal basin) is the object of research. The "Stepova" Mine borders in the north-west, north and north-east with the Chervonohrad sites No. 3, 5, in the east and south-east with the fields of the "Chervonohradska" and "Vidrodzhennia" Mines, and in the south with the "Lisova" Mine. In the "Stepova" Mine field, coal seams and interlayers occur in deposits of the Visean and Serpukhovian Stages of the Lower Carboniferous and the Bashkirian Stage of the Middle Carboniferous, where there are up to 56 coal interlayers and coal seams. In Visean Stage deposits, the minable thickness (0.95 – 1.15 m) is locally reached by seams v_0^3, v_0^4 in some areas, the thickness of the rest is 0.05 – 0.40 m.

The deposits of the Serpukhovian Stage, especially the upper part of the Bazhenov Formation, are characterized by the highest coal-bearing capacity. Coal seams having the greatest minable value, n_9, n_8^v, n_8, n_7^v, n_7, n_7^n throughout the entire area and v_6 in certain mine field sections, are confined to this section interval, and the main ones, n_8^v and n_7^n, are currently being mined. The thickness of other interlayers is in the range of 0.05 – 0.45 m. The Bashkirian Stage deposits contain up to 8 low-thickness coal interlayers, of which only b_1 seam reaches the standard thickness in local areas. This exploration wells and mining operations mainly confirm the nature of the coal-bearing capacity, specified contours of distribution and thickness, as well as the structure of coal seams.

The following is a brief description of the coal-bearing capacity of the assessed seams by area, taking into account their minable value.

Seam b_1 is widespread in the north-eastern part of the mine field, where it outcrops to the Carboniferous surface. With a simple structure, the seam retains a thickness of 0.50 – 0.65 m in the extreme northern part of the area in three isolated lenses. The seam has no minable value. As a result of this exploration, no significant changes have been found in the seam, and it is characterized as an irregular coal seam.

Seam n_{11} in most of the field has non-minable thickness or is absent. In some isolated, irregularly configured areas located along the contour of the seam outcrop to the Carboniferous surface, its thickness, with a simple structure, is 0.50 – 0.68 m, and in individual sections is 0.70 – 0.88 m. The seam has no minable value, because it is irregular. As a result of this exploration, no significant changes have been found in the seam, and it is characterized as an irregular coal seam.

Industrial seam n_9 in the western and southern parts of the mine field is absent as a result of extensive intraformational erosion. With minable thickness, the seam is spread over an area of 14 km^2 in the eastern part. In this area, the seam has a predominantly two-band structure and only in some wells in the south-western part – a simple structure. The useful seam thickness varies within 0.6 – 0.8 m, and the total thickness is 0.65 – 0.95 m. The thickness of the argillite interlayer separating the coal bands is 0.03 – 0.12 m, the upper coal band is predominantly thicker than the lower one.

3 Results and discussion

3.1 Determining the concentration of gases during coal gasification

Research on determining the concentration of producer gases during coal gasification is an important scientific-practical result for the development and improvement of gasification technologies. As a result of research, through the data obtained, it is not only possible to set optimal conditions to produce syngas, but also provide an opportunity for detailed analysis of various gasification process parameters, including the study of temperature conditions, zones of formation of reaction channels, the composition of raw materials suitable for gasification, etc. With this data, it is possible to determine the optimal combination of factors providing a high degree of conversion of coal or carbon-containing raw materials, for example, into synthesis gas with the lowest emissions of harmful substances.

This is particularly important in the context of ensuring environmental safety and compliance with environmental standards. In addition, these data make it possible to develop and improve processes for supplying catalysts to the underground gasifier reaction zones, which helps to increase the process productivity, while reducing its energy and material costs. Additionally, by analyzing the influence of various parameters on the gasification process, the quality of the resulting product and its suitability for further use in the production of various chemical compounds, fuel or electricity can be improved. Therefore, the study of determining the concentration of constituent gases during coal gasification is a key stage in the development and optimization of efficient and environmentally friendly technologies for converting carbon materials into valuable energy resources.

A wide range of application in blast mixtures of different gases, combined with the increased oxygen content (O_2) in the blast, provides selectivity of obtaining underground coal gasification products and stability of the coal seam gasification process, taking into account the mining-geological, technogenic and technical operating conditions of underground gasifiers.

The authors of the paper have studied the parameters of the producer gas yield during coal gasification, which is concentrated in the mine field main seams n_7^n and n_8^v of the "Stepova" Mine, SE "Lvivvuhillia" (Fig. 2). In this case, the study was conducted with variable blast mixture parameters: air blast (O_2 – 21% + N_2 – 79%); steam-air blast (O_2 – 15% + N_2 – 35% + steam – 50%), oxygen blast (O_2 – 35% + N_2 – 65%); carbon dioxide blast (O_2 – 15% + N_2 – 60% + CO_2 – 25%).

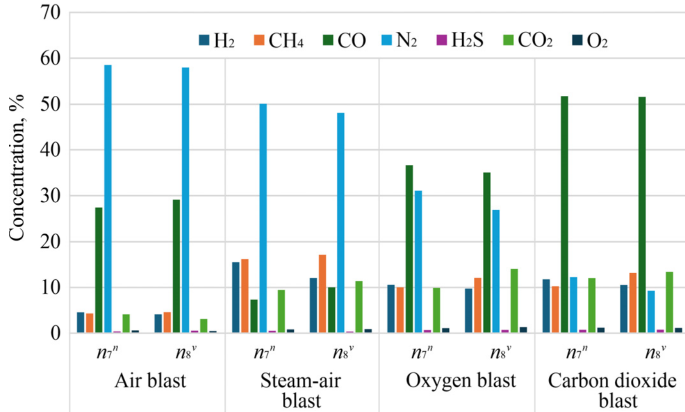

Fig. 2. Data on concentrations of ballast and combustible gases in the producer gas composition depending on the type of blast mixture supply and coal seam.

Studies to determine the concentration of the constituent coal gasification products from the "Stepova" Mine, SE "Lvivvuhillia" have shown that CO_2 is a constituent ballast component in the producer gas. Its concentration value from 4.12% to 14.12% is the primary CO reaction residue, which is formed in the oxidative zone. During the secondary reaction, CO will be formed in the reduction zone with the participation of carbon dioxide and carbon at a temperature of the gasifier channel walls of 800 – 1200 ºC. It should be noted that the heterogeneous reduction reaction of CO_2 to CO is a secondary gasification reaction. It takes place in the reduction zone of the underground gasifier and determines the resulting gas quality. At a temperature range of 940 – 1000 ºC in the underground gasifier, the CO concentration in the resulting gas increases, and the CO_2 content decreases. At lower temperatures of 400 – 500 ºC, on the contrary, the concentration of CO_2 increases and CO decreases.

In the course of the research, the parameters of the producer gas yield from 1 kg of coal have been additionally determined. The data on the producer gas volume depending on the type of blast mixture supply have been generalized (Fig. 3).

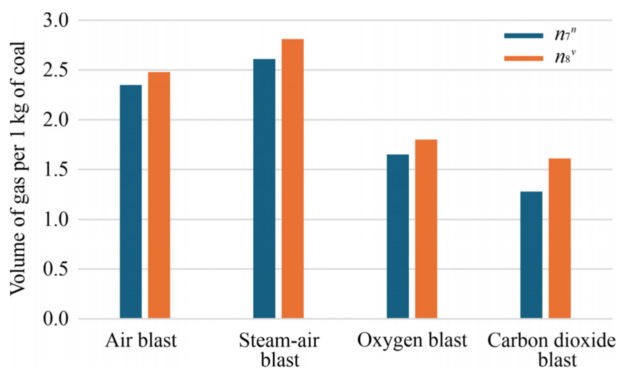

Fig. 3. Data on the producer gas yield depending on the type of blast mixture supply per 1 kg of coal.

Based on the data given in Figs. 2 and 3, the authors of the paper have found that when air blast is applied, the CO_2 emission is 0.1 m^3/kg of the n_7^n seam coal, and 0.07 m^3/kg of the n_8^v seam coal. The highest carbon dioxide concentration values in the producer gas mixture are present when carbon dioxide blast is supplied and are 0.15 and 0.22 m^3/kg of coal, respectively. At the same time, with a significant release of carbon dioxide, the producer gas calorific value during coal gasification of the n_7^n seam is 10.11 MJ, and for the n_8^v seam coal gasification – 11.4 MJ. When air blast is supplied, the calorific value is 4.73 MJ and 4.91 MJ of the n_7^n and n_8^v seams, respectively. Such a sharp increase in the calorific value is caused by a sharp increase in hydrogen concentrations from 4.56% to 11.76% for the n_7^n seam coal and from 4.12% to 10.55% for the n_8^v seam coal.

Low carbonic oxide concentrations (CO and CO_2) during air blast are due to nitrogen, which is an inert gas constituting approximately 79% of the air composition, entering the combustion face plane. Nitrogen does not form chemical bonds with other substances during the gasification process. This leads to a decrease in the partial pressure of carbonic oxide gases (CO and CO_2) in the reaction zone. This, in turn, creates conditions that facilitate the reduction of carbon dioxide (CO_2) to carbon monoxide (CO) and the formation of water (H_2O). But when high temperatures are reached in an underground gasifier, including over 1100 ºC, the carbon monoxide content in the source gas can reach much higher values, approaching 53%. This phenomenon is predominantly caused by the contact of carbon dioxide (CO_2), which is produced during gasification, with red-hot coal. Under high temperature conditions and involvement of coal as a catalyst, carbon dioxide can be reduced to carbon monoxide. The theoretical composition of the source gas in terms of carbon mono- and dioxides at a temperature of 1000 – 1100°C confirms this fact. Studies have revealed that the CO content can be as high as 52.9%, while the CO_2 content is negligible at only 3.13%.

3.2 Technological solutions for achieving climate neutrality in carbon dioxide utilization

Today, there are several proven technologies for carbon dioxide utilization [54]. The most widespread is the technology of capturing carbon dioxide from flue gases, followed by its catalytic conversion for further methanol synthesis [55]. However, major disadvantages of this method include the difficulty of providing stable conditions for the catalytic conversion process, to ensure pressure and temperature. Another well-known method is the technology of carbon dioxide utilization by its absorption by waste generated during combustion of solid fuels, where carbon dioxide reacts chemically with ash and slag waste [56, 57]. However, providing this process is conditioned by high energy costs for maintaining the carbon dioxide utilization unit. This is primarily due to the performance of additional technological operations, such as drying and grinding of raw materials for combustion.

A known technological solution is the preliminary separation of carbon dioxide from the target and by-products obtained during the thermocatalytic processing of solid fuel. Carbon dioxide is converted into a liquid state and further supplied to the bottom of a natural water body to a depth of 1 – 3 m, where the hydrogen sulphide content is at least 1.5 mg/l [58]. The main disadvantages of this technological solution are significant costs of carbon dioxide transportation. This is due to the use of land and sea transport at a distance from concentrated sources of its formation, limited locations for its utilization, which eliminates the risk of decomposition of carbon dioxide hydrates with subsequent its dissolution in sea water, which adversely affects marine flora and fauna.

The authors of the research propose a technology of carbon dioxide utilization by pre-separating it from the mixture of producer gas obtained during underground coal gasification. Fig. 4 shows a technological scheme of carbon dioxide utilization.

The underground gasifier is opened and prepared from the daylight surface *1* using the production blast injection and gas-outlet wells drilled through the solid fuel seam. After that, the solid fuel seam *3* is ignited and the process of its thermochemical processing is ensured by supplying the blast mixture through well *6*.

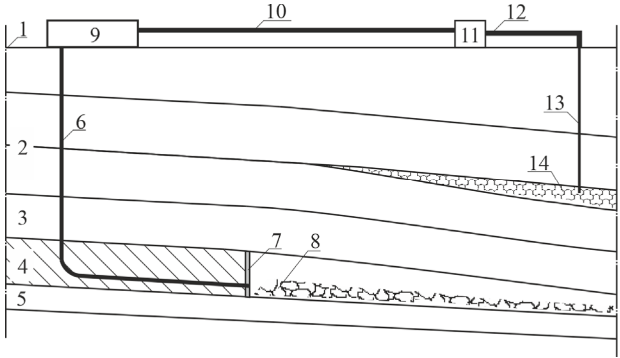

Fig. 4. Technological scheme of carbon dioxide utilization: 1 – a daylight surface; 2 – main roof; 3 – immediate roof; 4 – a solid fuel seam; 5 – the solid fuel seam bottom; 6 – a blast injection well; 7 – a combustion face; 8 – goaf; 9 – a producer gas cooling and purification complex; 10, 12 – a carbon dioxide removal pipeline; 11 – the carbon dioxide storage tank; 13 – utilization wells; 14 – the roof rock stratification zone of the underground gasifier.

The resulting producer gas from the gas-outlet well is delivered to the producer gas cooling and purification complex *9*, where combustible gases (CH_4, CO, H_2) are separated from associated ballast gases (N_2, CO_2, N_xO_x) and resinous substances. In this case, one of the known methods is used, such as with membrane plants.

After separation, CO_2 ballast gas is sent through pipeline *10* and stored in the carbon dioxide storage tank *11*. After that, it is subsequently utilized in the underground space by supplying it through pipeline *12* and utilization wells *13*, which are drilled to the stratification zone of the underground gasifier *14*. Stratification of the underground gasifier roof rocks occurs provided that the tensile strength of the rocks is perpendicular to stratification $G_t > R_t$, or the rock shear strength is parallel to stratification $\tau_s > R_s$. In the process of solid fuel gasification, zones of tensile and compressive stresses appear around the combustion face *7* along the length of the gasification column, which characterize a change in the rock mass stress-strain state.

Thus, above the goaf, the stratification cavities of the rock stratum are formed depending on the combustion face length, which are places for carbon dioxide utilization. At the same time, it should be noted that part of the CO_2 gas can be supplied to the combustion face through the blast injection well *6* as part of the blast mixture. Therefore, studies regarding the efficiency of the coal gasification process when supplied with the above-mentioned mixture are important.

Further research in this direction could focus on several areas to advance the understanding and application of underground coal gasification (UCG) technology for achieving climate neutrality in coal-mining regions. First, should be investigated methods to optimize the UCG process parameters such as temperature, pressure, and blast mixture composition to maximize syngas yield while minimizing emissions, energy consumption, and environmental impacts. Further must be analyzed the composition of syngas produced during UCG to understand its variability depending on factors such as coal type, seam depth, and geological conditions. Finally, research could support the development of demonstration projects and pilot studies to validate the technical feasibility, economic viability, and environmental sustainability of UCG technology in real-world conditions. By addressing these research areas, it is possible to advance the adoption of UCG technology as a viable pathway towards climate neutrality in coal-mining regions while ensuring environmental protection, socio-economic development, and energy security.

4 Conclusions

Increasing the concentration of carbon dioxide in the atmosphere is one of the primary drivers of global warming. The main source of carbon emissions is the combustion of fossil fuels such as coal, oil, and gas. Therefore, issues related to reducing the level of CO_2 emissions and their impact on the environment are urgent.

Ukraine, in the current realities of its fuel and energy complex, cannot afford to abandon coal as a type of energy raw material. This is primarily due to the complexity of transitioning to fully renewable energy sources due to its changing energy needs, especially after each shelling of critical infrastructure objects. Shelling and military actions lead to disruptions in electricity supply. Therefore, in such conditions, it is difficult to implement a planned transition to new energy sources. The authors of the paper focused on the implementation of an alternative coal mining technology at the site of its occurrence, namely underground coal gasification.

Indicators have been established regarding the release of combustible and ballast gases depending on the type of blast mixture supply to the underground gasifier. It has been determined that with air blasting, the concentrations of carbon oxides CO – 27.49 – 29.13% and CO_2 – 3.13 – 4.12% are the lowest. This is due to the ingress of nitrogen into the fire cut plane, which is an inert gas and does not form chemical bonds with other substances during the gasification process. When carbon dioxide is utilized as part of the blast mixture, the concentration of carbon oxide gases increases to 51.78% and 13.45%, respectively. The authors of the paper have proposed a technological scheme for carbon dioxide utilization, which could serve as the basis for climate neutrality in coal-mining regions based on underground coal gasification technology.

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