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An analysis of the potential use of methane from hard coal mines in a trigeneration system to reduce emissions into the atmosphere

Greenhouse gases and their emissions are issues that are being increasingly discussed due to climate change. Next to carbon dioxide, methane is considered one of the most important greenhouse gases. Reducing methane emissions could result in noticeable environmental benefits in a short time. Anthropogenic emissions constitute approximately 60% of total methane emissions and thus solutions to reduce emissions of this gas are most often sought in this sector. The subject of the study is the methane capture system in the "Pniówek" mine, belonging to the Upper Silesian Coal Basin (southern Poland), and the potential for methane management using a trigeneration system. The article discusses the utilization of methane from hard coal mines to reduce its emissions into the atmosphere and as a profitable solution to use the emitted gas. The authors describe a trigeneration system in which methane from the mine is burned in gas engines and used to produce electricity, heat, and cooling energy. This allows for reducing methane emissions into the atmosphere while increasing the efficiency of coal use. The article shows the results of measurements carried out in a hard coal mine in Poland. The presented example indicates the ecological and economic benefits resulting from the use of a trigeneration system.

Key words: *methane emission, emission reduction, economic use, trigeneration system*

1. INTRODUCTION

Methane has been recognized by the Intergovernmental Panel on Climate Change as the second most important greenhouse gas and thus it is necessary to focus on the reduction of its emissions. Progressing climate change has increased interest in greenhouse gas emissions and the potential to reduce them. The significant dominance of carbon dioxide in total greenhouse gas emissions has resulted in focusing attention on the sources of this gas in recent years but despite a much lower emission level, methane constitutes the most significant threat to the climate neutrality of the environment.

The amount of methane in the atmosphere has increased significantly over recent decades. The first increase was discernible in the 1980s. Then, after 1998, this value began to stabilize until 2008, when a significant increase in the concentration of this gas was noticed again, and this trend is being maintained. At the same time, it shows how important it is to introduce remedial measures in this area.

The sources of methane emissions may be natural or result from human activities. Natural sources include wetlands and peat bogs, while anthropogenic sources cover animal breeding, the energy sector (including activities related to mineral extraction), and waste landfills [1]. Anthropogenic emissions account for approximately 60% of total methane emissions.

There are many possible reasons for such an intense growth in methane content in the atmosphere. The dominant factor here is the increase in methane emissions in three sectors: energy, waste (including sewage), and agriculture [2]. Figure 1 shows the structure of global methane emissions.

a) b)

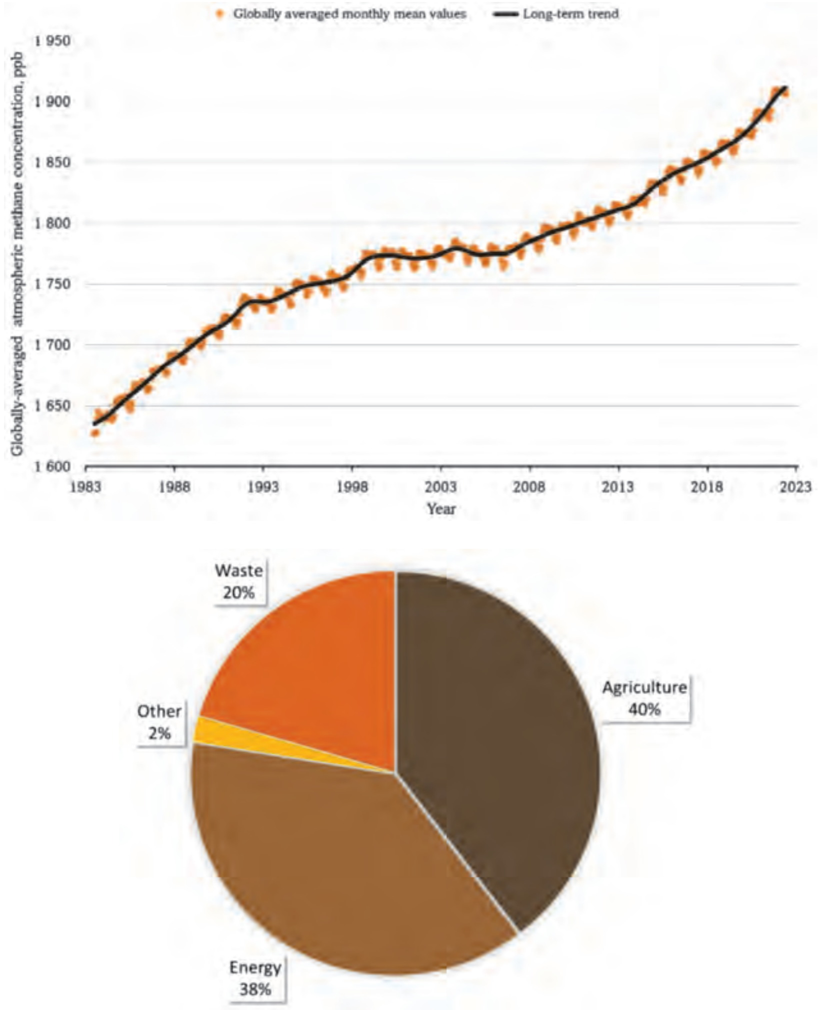


Fig. 1. Methane in the environment: a) global average monthly concentration of methane in the atmosphere, determined from sea surface areas in the years 1983–2022 – based on [3]; b) summary of methane emissions from anthropogenic sources by main sectors for 2020 – based on [4]

The global upward trend may be influenced by increased emissions in the agricultural, waste, and fossil fuel sectors in South and Southeast Asia, as well as growth in the fossil fuel sector in the United States [2]. However, Europe, where total emissions from anthropogenic sources constitute 7.4% of global methane emissions, is the only continent where methane emissions are constantly being reduced. For comparison, emissions occurring in Asia and the Pacific (excluding the Middle East and Russia) constitute 42.6% of the total methane emissions in the world [4]. According to data from the European Environment Agency (EEA), methane emissions in the EU-27 countries in 2021 were reduced by 37.4% compared to 1990, and, year by year, a decreasing trend in the observed values is noticed. Analyzing emissions over a shorter time horizon, it should be noted that the annual emissions decreased by 10.1% over ten years. Due to the already adopted climate policy strategies, the European Union is expected to be well on its way to reducing CH_4 emissions. According to the prepared scenarios [5], methane emissions are expected to decrease by approximately 20% in 2015–2030. Subsequent reductions in emissions will require the implementation of additional strategies in this direction. One of the global initiatives aimed at taking joint actions to reduce methane emissions is the methane agreement – The Global Methane Pledge (GMP), signed by over a hundred countries in 2021 during the COP26 climate conference. Today, 155 countries are participating in the GMP, which aims to reduce methane emissions by 30% from 2020 levels by 2030, which could slow global warming by more than 0.2°C by 2050.

The article focuses on using captured methane to produce electricity, heat, and cold in a trigeneration system in the example of the "Pniówek" mine. An analysis of the system's operating efficiency and, in particular, the possibility of using methane as a source of electricity production was presented. Detailed results include methane capture using the methane drainage system, gas concentration, and electricity production over six months.

2. METHANE EMISSION INTO THE ATMOSPHERE

2.1. Methane emission in Poland

As in the case of the analysis of the global situation, when considering the structure of methane emissions in Poland, the study started with the division into main sectors. A summary of methane emissions in Poland in 2020 is presented in Figure 2.

The most crucial sources of methane emissions in Poland include the energy sector, agriculture, and waste management. They account for 46.0%, 31.9%, and 22.0%, respectively. The first of these categories can be divided into two subcategories: fuel combustion and volatile emissions from fuels. The second category is noticeably dominant and is responsible for approximately 38.7% of total methane emissions in Poland. Focusing in detail on the energy sector, it can be noted that the predominant value of emissions comes from volatile emissions from solid fuels, which in 2020 are estimated at 579.1 kt.

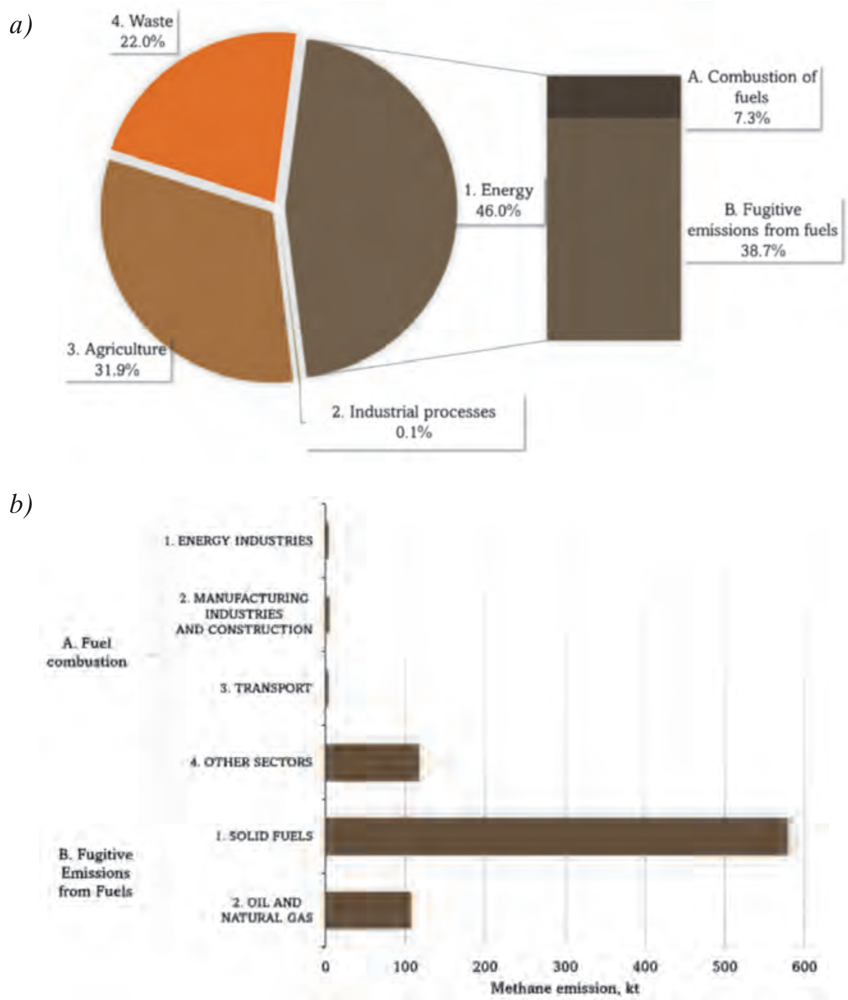


Fig. 2. Summary of methane emissions in Poland in 2020 – based on [6]: a) from anthropogenic sources according to main sectors; b) related to the energy sector

2.2. Characteristics of methane release into mining excavations

The nature of methane release into mine workings is very complex, as it depends on numerous geological and mining factors and changes in atmospheric pressure. Methane in coal deposits may occur in two forms: in free form, found in the pores and crevices of the deposit, and in the form of a gas physicochemically bound to coal. During mining, both coal seams and rocks surrounding the seam are relaxed and cracked, which leads to a growth in permeability and the release of methane from the relaxed zone into the goaves and workings. This is related to the disturbance of the pressure balance in the deposit, where the distribution of pressure changes in the rock mass is characterized by variability in time and space. The occurring pressure gradient causes the mass of gas to move towards the excavation, where the pressure is lower than the pressure of the gas in the rock mass. The stream of methane released into workings is defined as the total value of the amount of methane released from the mined seam, both from mined and transported coal and from the exposed coal bed of the working face, as well as emissions from neighboring seams located in the roof and floor and within the range of mining influences [7].

Many factors could significantly affect the intensity of methane emissions in a mining excavation. The most important of them include the method of deposit exploitation, the mining techniques used, the amount of extraction, and the selected method of ventilation and drainage of methane from the rock mass. Additionally, the operation of auxiliary devices to actively combat the methane threat or the impact of dams separating air currents will be crucial. Circumstances beyond human control will significantly influence emissivity including sudden drops in atmospheric pressure, the strength of roof rocks, or the occurrence of rock mass tremors.

Of the 20 hard coal mines operated in Poland, 19 are in the Upper Silesian Coal Basin. The only exception is Lubelski Węgiel "Bogdanka" SA, situated in the Lublin Coal Basin. In the period 2021–2022, 12 mining plants carried out extraction from methane deposits, where methane emissions were observed. At the same time, in 4 other mining plants, where work was also carried out in methane seams, no gas emissions were noticed. Exploitation in exclusively non-methane fields was carried out in 4 other mines. The principal source of methane capture in Polish mines is mining areas (64%), followed by methane captured on dams isolating goaves (34%). The share of methane drainage from drilled faces is very low (2%). The total absolute methane capacity in 2022 amounted to 778.95 million m^3/year, of which ventilation methane capacity accounted for 475.48 million m^3/year, while 303.47 million m^3/year was discharged through the drainage system. The methane drainage system uses 206.07 million m^3/year (68%). Captured gas from methane drainage systems is not always fully effectively used, which can be explained by the following factors: variable gas quality, insufficient technical infrastructure, as well as regulations and standards in this area. Therefore, the total emission of methane into the atmosphere in Polish mines is caused by the emission of methane from ventilation shafts (VAM) and the emission of unused methane from methane drainage. Currently, several projects on the capture and utilization of methane from rock mass are being implemented. Unfortunately, there are certain limitations in obtaining methane, especially from post-mining areas, related to the minimum concentration of captured gas of 30%. Therefore, as part of the Reduction of Methane Emissions Project – REM, the construction of a parallel methane drainage system with reduced gas concentration was proposed. The scope of work includes both the design and construction stages. In this way, a surface methane drainage station with a network of underground pipelines with methane intakes, a measurement system, and an automatic control system will be built in "Pniówek". Methane obtained from post-mining spoils will be utilized to produce electricity in gas engines connected to power generators. Another project being implemented is an intelligent methane drainage system, the aim of which is to optimize and improve the efficiency of the mine methane drainage system through its automation and digitization.

3. TECHNOLOGIES OF CAPTURE AND UTILIZATION OF METHANE

The techniques of methane drainage, capture, and use of gas in coal mines have been known for many years. Nevertheless, significant progress at the turn of the XX and XXI centuries has been noticed both in the advancement of technology and its application [8]. The principal purpose of methane capture is to ensure mine operation safety and continuity of mining operations. Methane drainage systems are designed to capture methane and discharge it outside the exploitation area or to the surface. Selecting an inappropriate method may result in low methane capture efficiency and/or low methane concentrations in the gas. However, we should not forget about environmental protection and increasingly higher requirements for reducing methane emissions into the atmosphere. Therefore, the management of captured methane and its effective utilization are becoming increasingly crucial. The efficiency of use is influenced primarily by an efficient methane drainage system, which ensures a constant methane concentration in the captured methane-air mixture. The demethanization station is automatically turned off when the CH_4 concentration drops below 30%. Therefore, attempts are being made to build an alternative methane intake installation with a reduced concentration of up to 20%. It is impossible to capture methane below this value due to approaching the upper explosive limit.

To increase the effectiveness and safety of methane capture, it is necessary to control and measure the methane concentration in the captured mixture in the methane drainage system. Thanks to ongoing control of methane concentration, it is possible to identify areas with an increased risk of growth in methane inflow or poor capture efficiency. It allows corrective and optimization actions to be taken to improve the efficiency of the entire methane capture system. In short, methane concentration control and precise measurement are essential to ensure safety and optimize methane capture processes. Monitoring measures are an essential part of any methane risk management strategy and enable effective actions to reduce emissions and optimize mining operations.

Various global trends in the demethanation of coal seams can be observed. Drainage through holes can be appropriately performed to capture methane from mining excavation, corridor workings, or post-mining excavation. The fundamental division according to the period of drainage of the rock mass includes forward methane release from coal seams untouched by mining operations (CBM – coalbed methane) and the current capture of gas released during mining activities (CMM – coal mine methane) [9]. Pre-methane demethanation is used for strongly methane-bearing, deep-lying seams with high permeability after already using the fracturing technique. This allows the seam to be degassed several years before operation. In pre-mining methane drainage, underground drilling in the coal seam and drilling from the surface can be used. The concentration of captured methane is approximately 90%. The effectiveness of this method is determined by appropriate gas permeability. Due to low seam permeability values, pre-mining methane drainage is practically not used in Polish conditions. Operational methane drainage in the mining excavation area is generally characterized by good efficiency, which results from the relaxation of coal seams during exploitation. The hole drainage methods used must be adapted to the ventilation method and the concentration of the captured methane is 40–50%.

Parameters characteristic of Polish hard coal mines in 2018–2022, including absolute methane capacity, the amount of captured methane, the efficiency of methane drainage, the efficiency of management of captured methane, and hard coal production, are listed in Table 1. The average efficiency of methane drainage in 2022 was 38.9%, which is lower than the value obtained in 2021. At the same time, an increase in the management efficiency of captured methane by over five percentage points was noted.

Methane from the drainage system can be used in various gas management solutions depending on the quality and volume flow of the discharged mixture. Known methods include gas combustion, supply into the gas network, use as an auxiliary or main source for energy systems, chemical input, or car fuel.

Table 1

The methane-bearing capacity in hard coal mines in 2018–2022 [10]

Parameter	Year				
	2018	2019	2020	2021	2022
Absolute methane-bearing capacity [million m^3/year]	916.1	803.8	819.6	815.3	778.9
Amount of captured methane [million m^3/year]	317.0	301.6	302.8	340.9	303.5
Methane drainage efficiency [%]	34.6	37.5	37.0	41.8	38.9
Efficiency of captured methane utilization [%]	64.1	62.8	62.1	62.8	67.9
Hard coal production [million tons]	63.4	61.6	54.4	55.0	52.8

The essential advantage of the popular solution of flare combustion is low investment cost and reduced methane emissions but this is at the cost of carbon dioxide being emitted into the atmosphere. Therefore, this method will be gradually limited or used mainly in emergencies. Introducing methane into gas networks requires high quality, including enrichment and expensive purification of the supplied gas. An increasingly frequently implemented solution is the utilization of methane as an energy source. Most often, this energy is used for the needs of a mining plant. It can be used as an additional fuel, for example, co-burned with other energy sources or as the primary fuel using engines, gas turbines, fuel cells, steam power plants, and other energy installations.

Purified and enriched gas can also be added to CNG and LNG. The main disadvantage of this solution, apart from the high processing, storage, and transport costs, is the need to meet the high-quality requirements of the obtained fuel [8]. In Poland, methane utilization methods are dominated by solutions related to energy production (mainly in gas engines) and co-combustion. The use of cogeneration systems to produce both electricity and heat is developing in particular dynamically. Combustion of captured methane is the simplest method of reducing CH_4 emissions. Direct combustion of methane is most often used only when there is no other option or in the event of a failure. Increasing the efficiency of gas management from methane removal is possible by assuring the stability of the composition of the methane-air mixture supplied to energy installations. The constancy of qualitative and quantitative gas parameters can be ensured by implementing appropriate activities, including controlling and regulating the methane removal process, supplying high-concentration gas from external sources, or purifying the mixture from inert gases [11].

A separate issue is the use of methane from ventilation air (VAM), where the main challenge is related to a significant stream of the mixture with low methane concentration. Therefore, it is necessary for the mine ventilation system to maintain the methane concentration below the lower explosive limit. The average methane content in ventilation air may vary significantly depending on the rock mass characteristics and the methane content in the coal seams. In the typical conditions of Polish mining plants, the methane content is usually 0.3% (it may be higher but never exceeds 0.75%). Due to the high ventilation airflow in mines, despite such low methane concentration values, a significant amount of methane is emitted into the atmosphere. It is estimated that approximately 70% of the total amount of methane released during mining works is emitted into the atmosphere through ventilation shafts. The solutions implemented so far on an industrial scale are mainly based on reducing VAM emissions through combustion, with other solutions being intensively developed in this area. Technologies that enable the enrichment of the methane-air mixture to methane concentrations are gaining popularity. Enriched gas with appropriate methane concentration could be used in existing devices that require higher contents of the flammable component in the mixture for proper operation [12]. The classification of methane management solutions divided into use as the main and auxiliary resource in a given technology is shown in Figure 3.

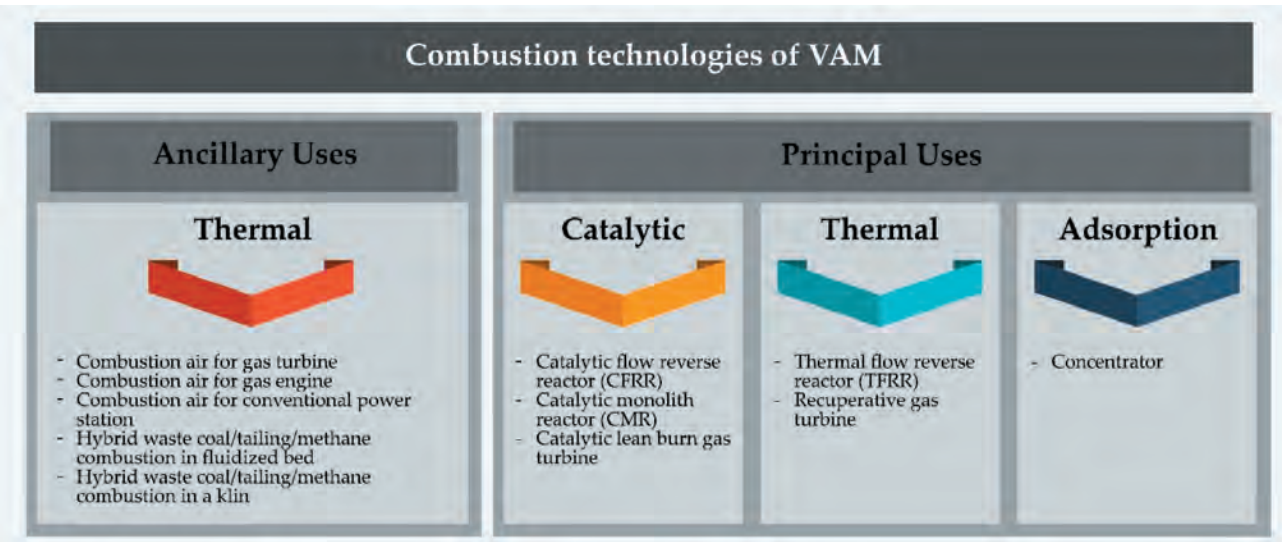


Fig. 3. VAM combustion technologies – classification and examples – based on [12]

4. ANALYSIS OF THE CASE OF CAPTURED METHANE UTILIZATION BY GAS ENGINES IN A TRIGENERATION SYSTEM

The subject of the analysis is the methane capture and utilization system in the "Pniówek" mine, located in the Upper Silesian Coal Basin (southern Poland). The study concerns the operation of a trigeneration system based on a gas piston engine powered by mine gas and absorption chillers. The engines produce electricity and heat whilst, on the cooling side, the system's task is to cool ventilation air in mining headings for the underground part of the mine. The installation diagram and device parameters are presented in Figure 4. Figure 5 shows the energy balance of the trigeneration system.

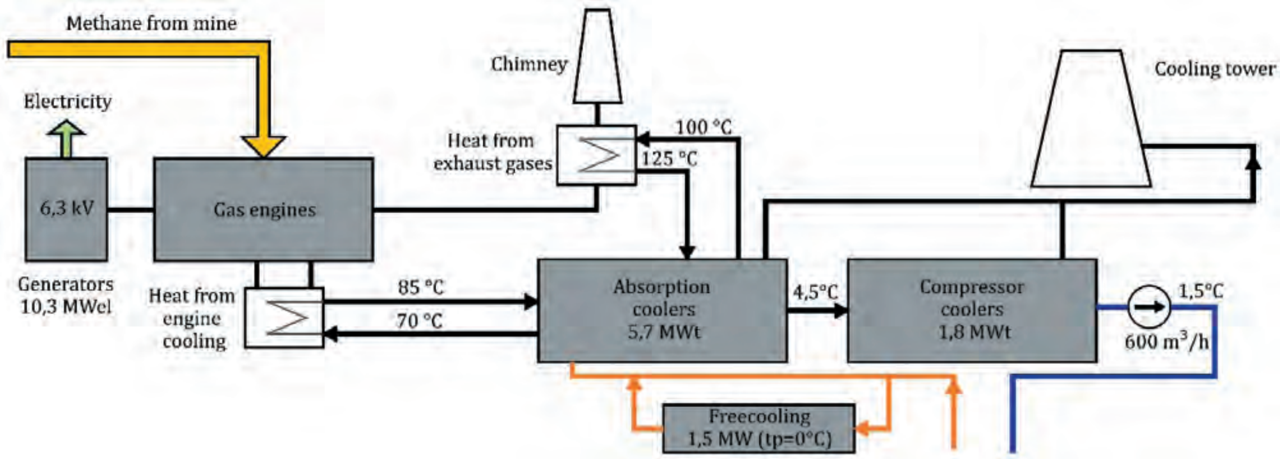


Fig. 4. Trigeneration system diagram – based on [13]

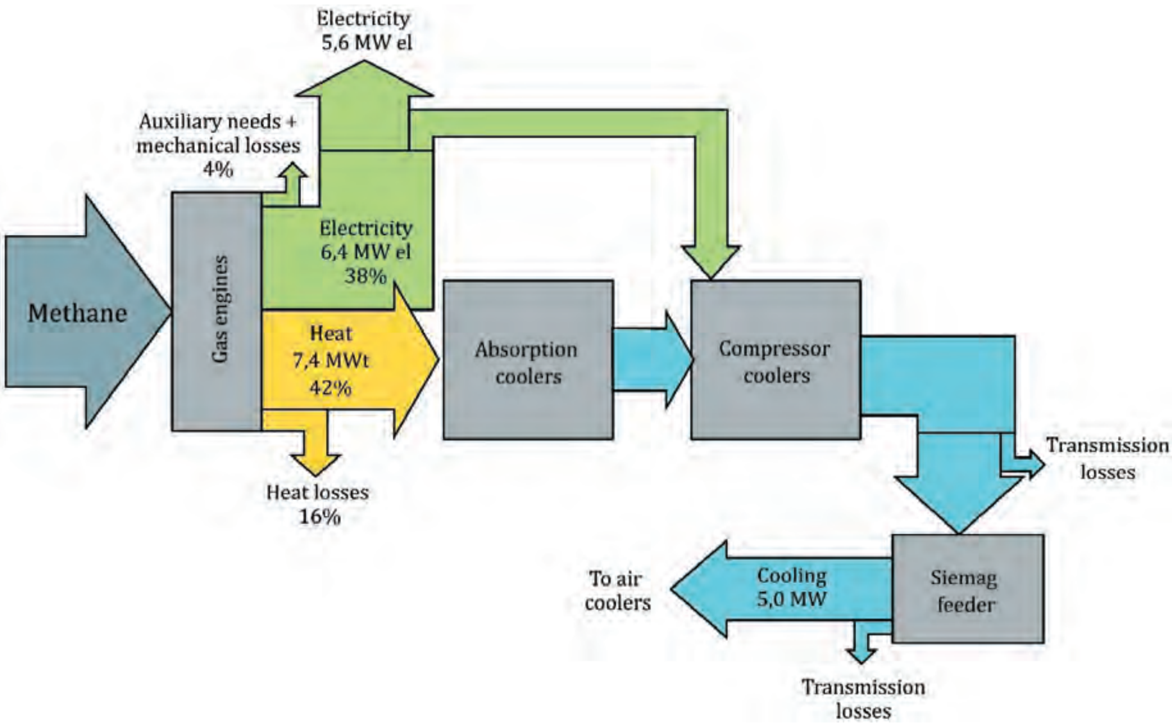


Fig. 5. Energy balance of the trigeneration system – based on [13]

4.1. Characteristics of the methane drainage station

The main element of the methane capture system is the drainage station. Its task is to create negative pressure in the methane drainage pipeline network and to transmit the captured gas from devices using methane. The methane drainage station can be divided into an installation on the suction side (1st compression stage), devices generating negative pressure and an installation on the discharge side (2nd compression stage), overpressure generating devices and auxiliary systems, including a gas cooling installation, regulating and safety devices, and control and monitoring equipment. On the suction side of the installation, there is also an exhaust chimney enabling gas to be discharged into the atmosphere under formation pressure in the event of a standstill of the methane drainage station. Due to the large amount of gas captured from the rock mass by the methane drainage station in the "Pniówek" mine, the methane-air mixture is pumped under different pressures to three receivers, i.e., gas engines, inter-mine gas transmission installation and heat and power plant, where the gas is burned and used for the mine's needs. The subject of further analysis is only methane combustion in a gas engine. The second compression stage is used to obtain the required gas pressure parameters on the transmission side to consumers after the methane drainage station.

The methane drainage station operates automatically, ensuring a stable pressure of gas sent to consumers. All impurities in the form of dust, water, or oil-water condensate are removed from the captured gas after the gas passes through the compressors, which allows the gas to be used to produce electricity and heat. Detailed operating parameters of the methane drainage station in the "Pniówek" mine are presented in the article [14]. A view of the methane drainage station with gas engines is shown in Figure 6.

a)

b)

Fig. 6. Methane drainage system in the "Pniówek" mine: a) methane drainage station [14]; b) gas engine

4.2. Measurement scheme

The combined energy and cooling system in the "Pniówek" mine is equipped with a measuring set that allows for the analysis of the parameters of the gas obtained from methane removal and the amount of electricity produced (Fig. 7). The presented results were collected in the period from January 1 to June 31, and mainly analyzed the stream of captured methane, the concentration of methane in the mixture, and the production of electricity. Readings were sampled every 15 minutes and then averaged on an hourly, daily, and monthly basis, respectively. Based on the results from the methane drainage station, an analysis of gas intake from methane drainage was carried out during the research period.

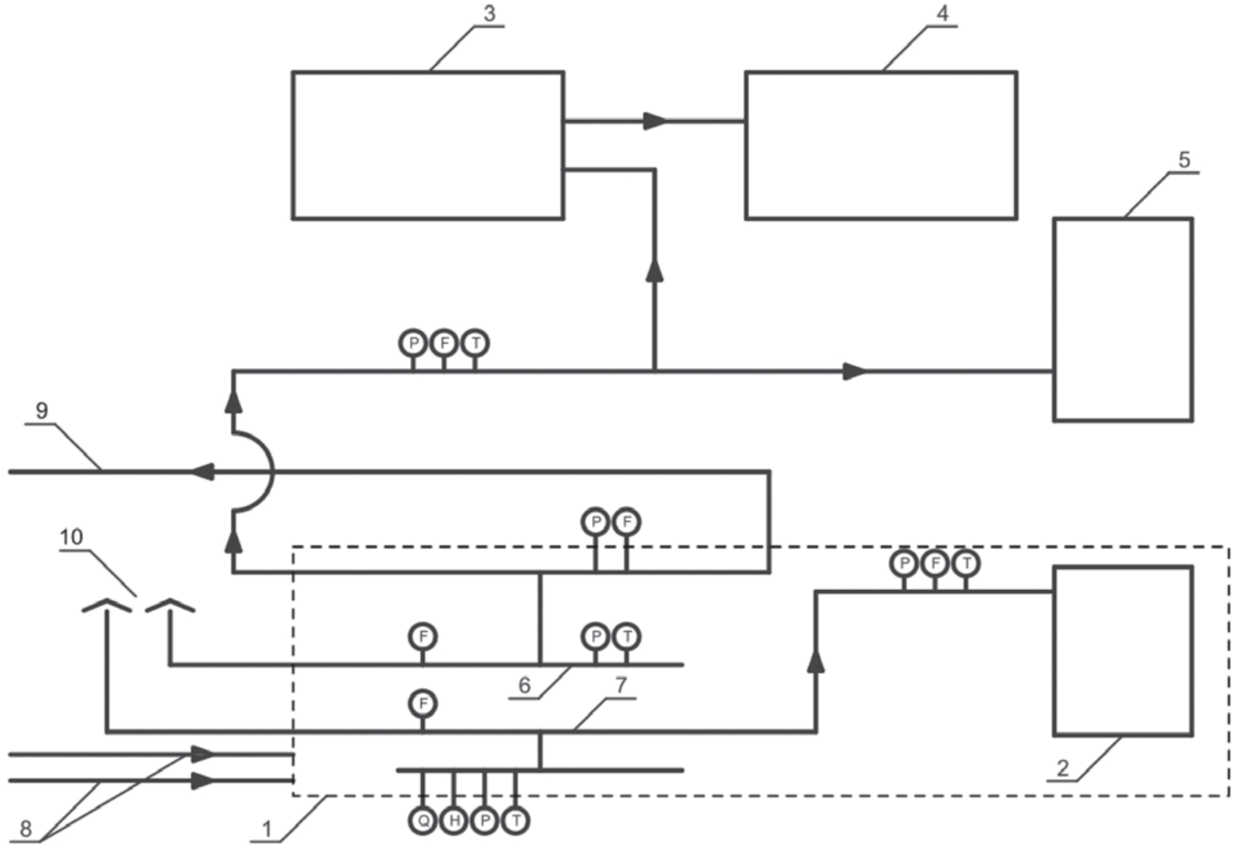


Fig. 7. Measuring system with sensor arrangement: T – gas temperature measurement; H – gas humidity measurement; P – gas pressure measurement; F – measurement of gas flow rate; Q – measurement of gas quality; 1 – methane drainage station; 2 – compressor hall; 3 – reduction station; 4 – heat and power plant; 5 – gas engines; 6 – 2nd stage of the pressure manifold; 7 – 1st stage of the pressure manifold; 8 – pipeline with methane-air mixture from a hard coal mine; 9 – inter-mine transmission installation; 10 – blowouts

4.3. Analysis and discussion of results

The results collected from the methane drainage station of the analyzed mine formed the basis for the presented study, which focused on the variability of gas intake and electricity production. The first stage of the work focused on the analysis over an hourly cycle, where the raw data was averaged over that time. The results are presented in Figure 8.

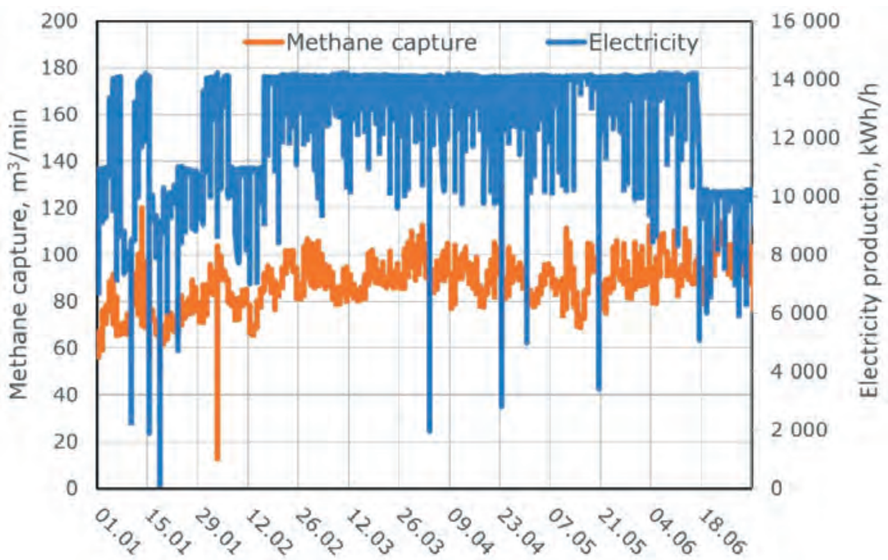


Fig. 8. Changes in methane capture and electricity production in an hourly cycle

With a methane-air mixture of 90–100 m^3/min, electricity production of 14,000 kWh/h was achieved while reducing the methane intake to 60–70 m^3/min results in electrical production lowering to 11,000 kWh/h.

To use the captured mixture in the system described above, it is crucial to maintain the appropriate methane concentration in the methane-air stream. Therefore, the concentration of this parameter was also analyzed, and the course of variability is shown in Figure 9. The graph shows that the methane concentration remained at an average level of approximately 60%.

Figure 10 shows changes in the methane concentration, electricity production, and the mixture capture after daily and monthly averages in the analyzed period.

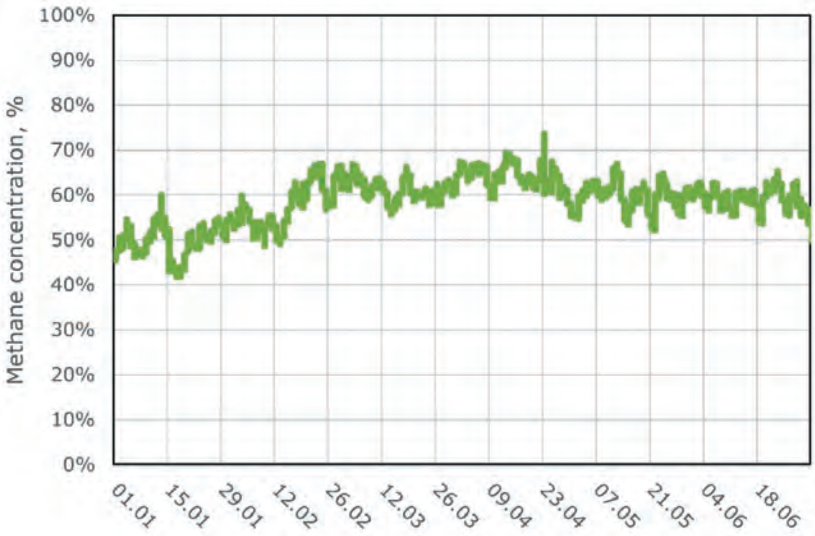
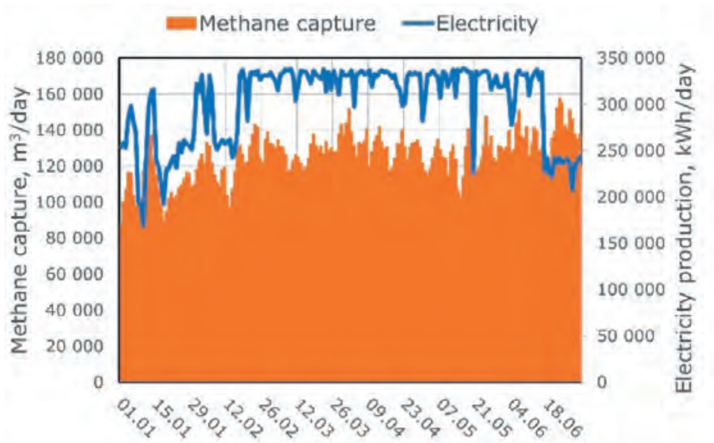


Fig. 9. Changes in methane concentration in the mixture

a)



b)

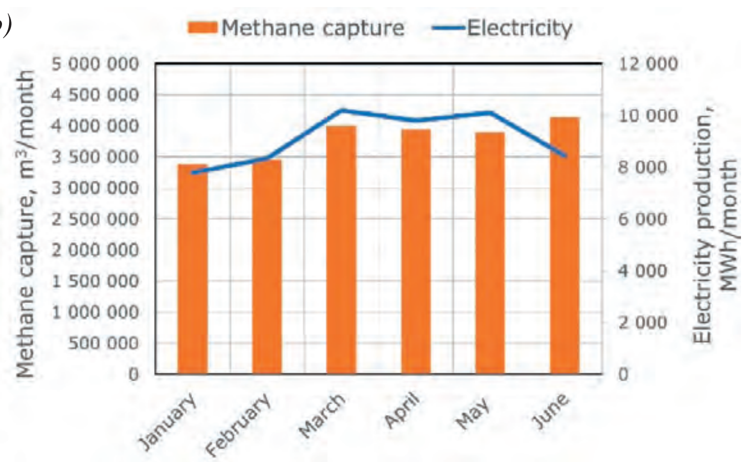


Fig. 10. Variability of methane capture in the first half of the year: a) in the daily cycle; b) on a monthly basis

In the first half of the year, the monthly methane capture varied from 3.3 to 4.2 million m^3 per month, resulting in electricity production from 7.7 to 10.2 thousand MWh per month. Methane emissions in this amount correspond to approximately 55–65 thousand tons of CO_2eq, assuming a GWP of 25. As a result of methane combustion, carbon dioxide is released into the atmosphere in larger quantities than the methane supplied to the process. By burning every ton of methane, 2.75 tons of carbon dioxide are emitted. Due to the much lower impact of this gas on the greenhouse effect, despite higher emissions, this process has a much smaller impact on the atmosphere compared to the emission of pure methane. With such significant methane emissions into the atmosphere during mining, methane combustion plays an essential role in reducing the greenhouse effect.

4.4. Proposal of a comprehensive approach to the management and economic use of methane

Applying best practices in demethanization and methane utilization is crucial to reducing methane-related incidents that too often accompany coal mining and contributing to environmental protection by reducing greenhouse gas (GHG) emissions [8].

The lack of effective management of the production and distribution of electricity/heat/cooling energy makes it impossible to exploit coal seams with high methane and climatic hazards, and unmanaged methane emissions cause environmental damage but also involve emission fees, which will pose a problem with the profitability of mining in the future. Hence, a comprehensive approach to the issue of methane capture and its optimal management is especially crucial. Figure 11 shows a diagram of a comprehensive approach to the challenge of methane capture and utilization.

The first stage in the adopted procedure was a detailed understanding of the source of methane in the analyzed mine, i.e., the predicted emission to the mine workings and/or the atmosphere. Recognition of resources is necessary to select gas capture and use techniques. The next step concerns the optimization of the chosen methane capture method by increasing the quantity and quality of the captured gas. Based on the first two stages, it is possible to develop the conception of methane capture and management in the next stage and then implement the project. However, this is not the last stage in the appropriate management of methane emissions in the mine since one of the most important is the proper operation of the system. This mainly relates to the ongoing analysis of changes in methane availability, monitoring the parameters of the captured mixture, training staff in the proper system operation, and systematic maintenance.

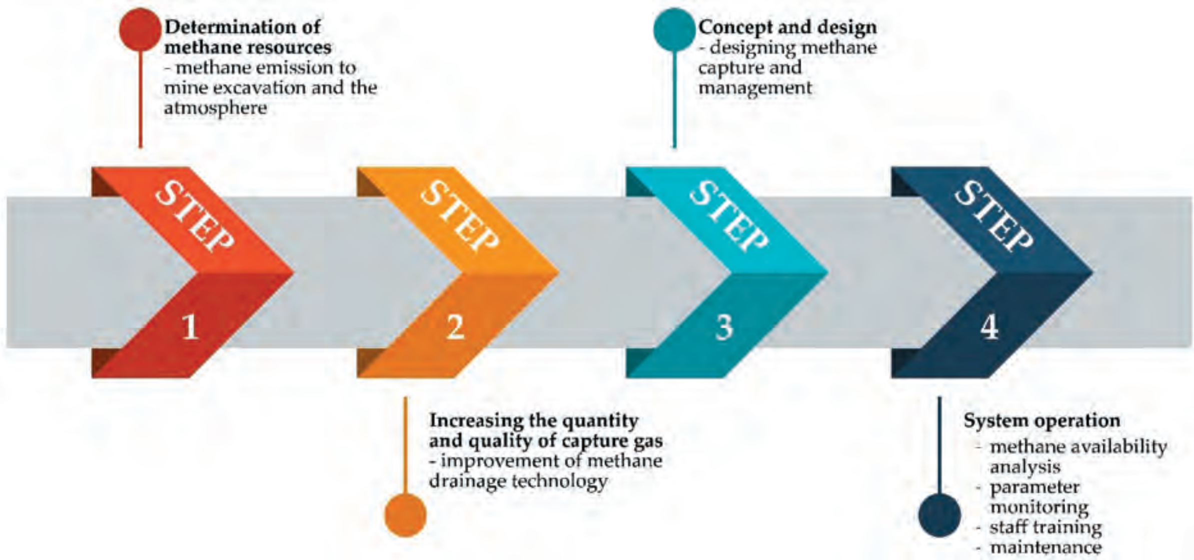


Fig. 11. Scheme of a comprehensive approach to the issue of methane capture and management

5. SUMMARY

Methane emissions from mines have been of great interest for years. This is a crucial topic, not only for environmental reasons but also for energy and, therefore, financial benefits. Poland, along with the United States, Russia, Australia, Ukraine, Kazakhstan, and India, is one of the countries with significant CMM emissions.

To ensure professional and effective risk management, good practices in mining need to be transferred to all countries. Regardless of the location or mining conditions, it is possible to significantly reduce the risk of methane incidents and explosions. Effective management of methane risk in coal mines can also have the benefit of contributing to the reduction of greenhouse gas emissions. The trigeneration system in which methane from the mine is burned in gas engines and used to produce electricity, heat, and cooling energy is an example of reasonable and optimal management. This allows for reducing methane emissions into the atmosphere while increasing the efficiency of coal mining in conditions of methane and climatic threats.

The article presents the results of the study carried out in a hard coal mine in Poland. This example is used to indicate the ecological and economic benefits resulting from the trigeneration system. The monthly methane capture ranges from 3.3 million m^3 to 4.1 million m^3. It corresponds to monthly electricity production from 7,790 MWh to 10,190 MWh. This methane emission in CO_2 equivalent is approximately 55–66 thousand tons of CO_2eq.

In summary, it should be stated that methane utilization from hard coal mines in a trigeneration system is a potential solution to effectively reduce methane emissions into the atmosphere. However, to achieve this goal, it is necessary to ensure the appropriate concentration and amount of methane captured by the methane drainage system. These parameters are crucial elements of an effective methane emission reduction strategy in the coal sector.

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