Utilization of methane deposits from the liquidated mines in the aspect of environmentally friendly energy technologies

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Abstract. At the beginning of the article main factors occurring in polluted atmospheric air and their connection with the methods of energy production are discussed. Various energy sources in the aspect of energy production technologies, including primary energy sources are presented. Two main actions taken to improve the quality of atmospheric air in Poland are described: Clean Air Programme, assuming a subsidy for an exchange of individually-used coal boilers for ecological ones or for gas heating, and the Polish Energy Policy until 2040, which assumes a gradual reduction in the share of hard coal and lignite in energy production. Methane as a mineral accompanying coal seams as well as ways of its recognition and management are presented. An example of the conducted research project shows a significance of the resource recognition and dynamics of the deposit in planning an economically justified exploitation of the deposit from closed down mines. Finally, there is hope that due to a further process of efficient restructuring of the Polish mining industry, the importance of using methane from closed down mines as a green energy source will increase.

1. Introduction
An environmental protection, including the fight against smog, gains more and more importance in the European Union. In Poland, a need to take such actions is confirmed by a control carried out by the Supreme Audit Office [1], which shows that the main cause of insufficient air quality in Poland is the emission of suspended dust and benzo(a)pyrene from domestic furnaces and local coal-fired boilers. The concentrations of benzo(a)pyrene, which should be at most according to WHO standards (World Health Organization) 1 ng/m³ of air, are exceeded in Poland more than eight times. A slightly better situation - as reported by the Supreme Audit Office - is in the case of PM10 and PM2.5 air pollution, although their concentrations vary in different parts of our country. Therefore, as regards heating buildings and houses, the government of the Republic of Poland encourages a replacement of old boilers with more ecological ones, as well as home insulation under the Clean Air Programme [2], for which PLN 103 billion are allocated. Replacing furnaces and introducing thermo-modernization of houses are aimed at improving the energy efficiency of single-family buildings and reducing an emission of dust to the atmosphere.

It should be emphasized, however, that these are not the only actions aimed at reducing the so-called low emission, mainly due to the fact that environmental protection is not conducive to energy production from solid fuels. The energy system in Poland is based on hard coal and lignite. Therefore, the government of the Republic of Poland undertakes measures aimed at abandoning a production of...
energy from these raw materials, through increasing a share of pro-ecological energy, including the energy produced from natural gas and nuclear energy [3].

If a possibility of using methane as the so-called clean fuel is considered, although the scale is relatively small - it is also worth using it even on such a small scale.

2. **Plan of energy sources**

A development of science and technology has caused that for a production of energy, people use many solutions, including the basic energy sources occurring on the Earth, such as the sun, water or wind, i.e. renewable sources [4]. Among them, technologies allowing a separate generation of electricity and of thermal energy, as well as technologies generating both electricity and thermal energy, are distinguished - Table 1.

Table 1. Type of produced energy in the context of energy production technology [4]

| Type of produced energy | Technology of energy production | Primary source of energy |
|-------------------------|---------------------------------|--------------------------|
| electric                | water power plants              | water                    |
|                         | wind power plants               | wind                     |
|                         | power plants using ocean currents| sun - heating ocean waters, Earth, atmosphere |
|                         | photovoltaic cells and solar power plants | sun - solar radiation |
|                         | tidal power plants              | gravity - tidal waters associated with the moon phase |
| thermal                 | heat pumps                      |                          |
|                         | collectors and thermal          | sun - solar radiation    |
|                         | solar power plants              |                          |
| electrical and heat     | wind power plants               | wind                     |
|                         | combined heat and power plants  | sun - biomass            |
|                         |                                 | Earth- geothermal sources |
3. **Pro-ecological activities in the energy generation sector**

As it has already been mentioned, some actions have been taken in Poland aimed at moving away from hard coal and lignite energy generation to increase the share of pro-ecological energy. The first but significant results are to be experienced until 2040, which is reflected in the document "Energy Policy of Poland until 2040" (PEP2040) [3]. It is a strategy setting directions for a development of the energy sector - including the tasks necessary for an implementation in the short-term - in full compliance with the European Union strategic documents.

The forecasting data included in PEP2040, are the result of optimization modelling of the shape of the power balance in the 2040 perspective, taking into account (among others) an increase in installed net power from about 40 GW to 72.6 GW in 2040 and an increase in electricity production from approx. 165 TWh to 232 TWh in 2040. PEP2040 assumes that it is impossible to deviate from fossil energy sources completely. However, it is assumed that there will be an optimization of the use of domestic energy resources, based on a rational use of energy resources, i.e. hard coal, lignite, natural gas, crude oil, biomass and non-agricultural waste, ensuring, inter alia, a profitability of the mining sector, a rational exploitation and innovations in an extraction and use of raw materials. The need to expand a generation and network infrastructure of electricity producers was also taken into account, aimed at covering the demand for electricity with generation capacities, other than conventional coal in a stable, flexible and ecological way.

Drawing attention by the PEP2040 creators to a development of cogeneration gives hope for increasing the scope of activities related to obtaining methane and its economic utilization.

![Figure 1. Primary energy acquisition [6].](image)
4. Methane as a source of energy

Currently in Poland, for the energy production - although on a small scale - methane is also used. It is a mineral accompanying coal seams. However, to use it, it must be captured earlier, which it can be done in several ways, depending on what kind of coal deposit and the geological and mining environment are involved.

Due to the method of capturing coal seam methane, [7] the following cases can be distinguished:
- methane from coal seams unaffected by mining exploitation, i.e. Coal Bed Methane (CBM), which is obtained before starting the operation of a given seam,
- methane coming from coal seams disturbed by exploitation, released to mining excavations during hard coal mining, i.e. Coal Mine Methane (CMM), which is partially captured by demethanization of the deposit, and partly released into the ventilation air (Ventilation Air Methane - VAM),
- methane from coal seams, released after their exploitation to mine workings, so-called Abandoned Mine Methane (AMM), located in the areas of liquidated mines.

In Poland, due to a very low carbon permeability of the Upper Silesian Coal Basin, methane is not included in the pre-operational phase (CBM). However, methane content is relatively high in the operational and after-operational phase (CMM). According to the data of the Industrial Development Agency [8], an increasing amount of separated methane (CMM) is captured by surface demethanization stations - in 2016, approx. 346.6 million m$^3$ were captured. Some of this amount of methane is consumed by mining enterprises - in 2016 it was 47.6 million m$^3$ - which enabled to produce over 270.3 thousand MWh of electricity and almost 760.3 thousand GJ of heat.

However, as regards the production of energy, statistical data do not include information about the use of methane from liquidated mines, probably because it is negligible in the total amount of energy production. The fact is that an interest in such methane acquisition increases - in 2012 there were two mining plants in Poland operating AMM, in 2017 - three, and an exploration and identification of methane deposits from coal seams were conducted in Poland on the basis of eight concessions granted by the Minister of the Environment. The gas, extracted from liquidated mines, is managed either directly by the methane extraction plant or after transferring it to the entrepreneur who deals with the generation of energy in cogeneration aggregates.

It should also be added that in contrast to the 1990s, when during the intensive restructuring of the Polish mining industry, there was no vision of methane use after a liquidation of mines, now this issue is already addressed at the mine decommissioning planning stage. There is a chance to develop system solutions for AMM gas recognition. It seems to be justified in every respect, as the number of mines planned for liquidation will constantly increase. This will be served by the mentioned entry in PEP2040, referring to methane, which will probably cause an interest in AMM gas to increase even more. This is also served by the amendment to the Act on the Functioning of Hard Coal Mining and the Act Amending the Geological and Mining Law and Certain Other Acts, introducing solutions to facilitate a development of methane obtained from hard coal deposits within a liquidated mining plant or its designated part [9]. This facilitates an extraction of methane from coal seams (as an accompanying mineral) of liquidated mines, which means that a mining enterprise, dealing with the liquidation of mines, does not have to have a hydrocarbon license for obtaining methane from liquidated mining plants or their designated parts. This will facilitate a development of methane exploitation, while at the same time ensuring the safety of neighbouring mines and the environment.

5. Economics of using methane from liquidated mines

Current experience shows that the best way to develop AMM is to generate energy in cogeneration aggregates, which are highly specialized devices for combined production of electricity and heat. Usually it is a combination of an internal combustion engine, a generator, a set of heat exchangers and a control system that allows the unit to be controlled locally, remotely via a computer or a mobile phone. Contrary to other alternative ways of producing electricity, the greatest benefit of using a
cogeneration is that it is possible to produce as much energy as it is needed at a given moment. For this reason, cogeneration is sometimes referred to as a controlled source of energy.

However, energy production in CHP cogeneration aggregates must be economically justified, which is influenced by many factors. One of them is the time of potential efficient extraction of methane from a given deposit.

The energy production planning in cogeneration aggregates is based on a lot of data - regarding both the parameters of the cogeneration aggregates and the parameters characterizing the methane deposit. For example, if the extracted methane would be consumed in the ENGINE Caterpillar 3516 1.136 MW, its optimal performance parameters should be taken into account - combustion of 5 m$^3$/min gas at 100% CH$_4$ - and limit tolerable performance parameters - combustion of 15 m$^3$/min gas with a minimum concentration of 33% CH$_4$, as well as an economically optimal engine operation time - min. 8,400 h/year. These parameters set the right requirements for methane resources in the reservoir, while the exploitation resources, understood as 67% of industrial resources, are more important than industrial resources. Only such resources, due to limitations of the minimum methane concentration, can be used in an internal combustion engine in its continuous, safe operation [10].

6. **Dynamics of the methane deposit as a determinant of the method of exploitation**

It is important to adopt an appropriate business model for the effective exploitation of the AMM methane deposit when planning energy production in cogeneration aggregates. It is about the choice of the deposit extraction method: stable - long-term, realized with one aggregate, at specific fixed costs, or dynamic - short-term, implemented with the use of two or more aggregates, with other fixed costs. However, to conduct such considerations, the methane deposit should also be recognized in terms of its dynamics.

In the case of a seam with gas collecting features - and a vast majority of deposits in closed down mines have such features (due to an occurrence of unsubstituted, uninhabited mine workings) - exploited with one bore-hole, e.g. A bore-hole first methane deposit performance ($W_{2d}$) [m$^3$/t] is determined from [11]:

$$W_{2d} = (W_p \cdot p_m)$$  \hspace{1cm} (1)

where: $W_p$ - efficiency of the gas pumping station (amount of gas extracted from the bore-hole) [m$^3$/t], $p_m$ - methane concentration in the captured gas [%], $t_i$ - time unit [year/day/h/min].

Next, the dynamics decrease rate in methane concentration in the captured gas ($Q_{pm}$) [% / $t_i$] is determined from:

$$Q_{pm} = (p_{pm} - p_{km}) : t_i$$  \hspace{1cm} (2)

where: $p_{pm}$ - methane concentration at the beginning of the period under assessment [%], $p_{km}$ - methane concentration at the end of the rated period [%].

Otherwise, it should be followed in the case of the management of methane obtained with the A bore-hole, with a parallel independent exploitation (by another entrepreneur) of the second bore-hole. The specificity of this issue will be presented on the basis of the research and development work [11].

In the presented case, apart from the objective bore-hole A, located in less favourable conditions occurring in the western part of the gas collector, there was bore-hole B, located in more favourable conditions, in the central part of the collector - with higher capacity, which also exploited methane, but by another entrepreneur. In order to determine the performance dynamics of the A bore-hole for the optimal use of the AMM methane deposit for cogeneration engines, several tests were carried out, using an additional flare gas combustion plant, to which methane was supplied through a branch.
mounted at the gas collection site (with a cogeneration aggregate). This ensured a parallel gas collection by the engine working in the aggregate - with a flow of methane to it in the amount of 5 m$^3$/min - and gas flow to the torch, which imitated the second cogeneration unit. Prior to the tests, the transfer capacity of the A bore-hole was about 880 m$^3$/h, and the methane concentration in the captured gas was about 61%.

To illustrate the method three incidents influencing the layout of the deposit - gas combustion, were selected from the tests, mainly due to the fact that they enabled to recognize the deposit during unusual phenomena, occurring from time to time. Two incidents were related to an operation of the pressure transfer station, one – causing a necessity of limiting the flow of captured gas through the torch to approx. 840 m$^3$/h to maintain the minimum pressure needed to operate the generator. The results of these tests indicated that in addition to the incident periods, there were changes regarding:

- the amount of captured gas - from 880, through 890 to 782 m$^3$/h,
- gas temperature - from 36.56, through 40.6 to 38°C,
- head vacuum - from -8.81, through -8.95 to 8.89 kPa,
- methane concentration - from 61.14, 62.82 to 51.95%.

as shown in Figures 2 and 3.

**Figure 2.** Illustration of changes in methane yield and concentration in bore-holes A and B [11].

**Figure 3.** Illustration of the dynamics of changes in the concentration of methane captured by holes A and B during the testing period [11].
The tests, simulating an operation of two cogeneration engines on bore-hole A, showed as follows:

- it is possible to increase the methane extraction with the A bore-hole to the level limited by the pumping station efficiency and limited by the decreasing methane concentration,
- it is impossible to operate the pumping station with maximum efficiency over a longer period of time,
- there was an increase in gas production from bore-hole A:
  - an operation of two cogeneration engines affected the decrease of methane concentration, while the decrease dynamics is lower than the decrease dynamics occurring before and after the experiment,
  - an operation of two cogeneration engines forced the inflow of gas to bore-hole A from a slightly further distance from the bore-hole, mainly from the east, where methane concentration is higher,
  - an operation of two cogeneration engines affected the minimum decrease in the concentration of methane on the B bore-hole,
- the tests confirmed a stabilization of the parameters of the gas extracted after the tests were completed on the bore-hole A in principle within an hour, with the methane concentration stabilizing at a lower level by approx. 2% in relation to the level immediately before the tests,
- an increase in the volume of captured gas on the bore-hole A causes a significant drop in the methane concentration - the dynamics rate of methane concentration drop during the experiment reached the value of 2.4% CH₄/ day, and was 8 times higher than the value of the methane drop indicator for stabilized work for one cogeneration engine (from the period before the tests), amounting to 0.2987% CH₄/day.

These applications were used for planning the exploitation method, which resulted in a selection of a stable, long-term use of AMM gas for energy production.

7. Summary

Undertaking activities, aimed at improving the environmental conditions of the Polish society, results from the diagnosis of the current bad condition of atmospheric air in many cities, which is the result of suspended dust and benzo(a)pyrene from domestic furnaces and local coal-fired boilers.

The actions of the Polish government related to, among others, subsidies for exchanging coal boilers for individual power generation for ecological boilers and gas heating, as well as to an implementation of the Polish Energy Policy until 2040, assume a shift from hard coal and lignite as the basic sources of energy.

In the diversification of energy sources, methane also has a role to play, including the methane obtained from liquidated mines.

Planning of economically justified energy production in cogeneration aggregates requires an identification of the methane deposits in liquidated mines in terms of exploitation resources and deposit dynamics.

A diagnosis of the bed dynamics, requiring research and tests to simulate the AMM gas intake by two production units, enables to choose correctly one of the two methods of reservoir management: stable - long-term or dynamic - short-term, implemented with the use of two or more cogeneration aggregates.

A gradually reduced share of hard coal for energy production will result in a liquidation of subsequent mines, which should increase the share of AMM gas in the pro-ecological energy production.

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