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The most important factors contributing to the effective development of abandoned mine methane resources in the Upper Silesian Coal Basin

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Abandoned mine methane (AMM) is a by-product of the underground mining of gassy coal seams. Closed and abandoned mines have the potential of accumulating gas which is continuously released over many years after the end of mining. The commercial development of AMM resources is beneficial because economic profits are combined with environmental and safety benefits. Since several gassy coal mines have been closed in recent years, a considerable AMM potential may exist in the Upper Silesian Coal Basin (USCB). To assess AMM resource potential in the USCB, a research project was conducted by the Upper Silesian Branch of the Polish Geological Institute – National Research Institute (PGI-NRI). The project revealed deficiencies in the existing approach to the AMM resource evaluation methodology, and thus a new dynamic method of AMM resources/reserves estimation was developed. The new method was used to estimate the AMM reserves of the seven abandoned mining areas considered prospective for AMM development in the USCB. The results demonstrated that the recovery and utilization of AMM is poorly developed in the USCB. Only three commercial AMM development projects have been implemented over the last 20 years, with a cumulative production of 70 million m^3. An understanding of factors contributing to the effective development of AMM resources is important for the long-term planning of AMM utilization in the USCB. Four groups of these factors have been identified based on the PGI-NRI project findings and each group is discussed in detail in this paper. The factors of the first group refer to the knowledge of geological and structural conditions which control permeability and methane content distribution in the basin. The remaining three groups of factors are related to breaking down existing barriers that have common roots in the legal and administrative system, in which appropriate changes are proposed in this article.

Key words: coalbed methane, coal mine methane, abandoned mine methane, Upper Silesian Coal Basin, methane emission reduction.

INTRODUCTION

When a gassy coal mine is closed, coal-related gas is a major hazard in terms of public safety (uncontrolled migration of gas to the surface) and the environment (methane emission to the atmosphere). However, coal-related gas can also be a valuable energy source if properly and efficiently captured and used.

The term coal-related gas, commonly referred to as coalbed methane (CBM), includes all types of gas accumulations derived from coal, but, depending on the form of occurrence and gas extraction technology, it can be divided into naturally occurring gas accumulation referred to as virgin coalbed methane (VCBM) and anthropogenic gas accumulation, which is formed as a result of coal mining, referred to as coal mine methane (CMM). CMM is gas released during coal mining, which is partially captured using an underground drainage system. A subtype of CMM is ventilation air methane (VAM), which is methane emitted through ventilation shafts at a very low concentrations. When a gassy coal mine is closed, the remaining CMM gas is referred to as abandoned mine methane (Fig. 1). AMM is post-closure methane gas stored and released over many years within an area disturbed by mining. AMM gas can be extracted using surface-to-gob wells (wells drilled from the surface directly into goaf areas in order to extract methane gas) or, less frequently, using an existing underground methane drainage system.

Commercial development of AMM is almost always a challenge due its occurrence in post-mining areas along with relatively low production flow rates (compared to conventional gas

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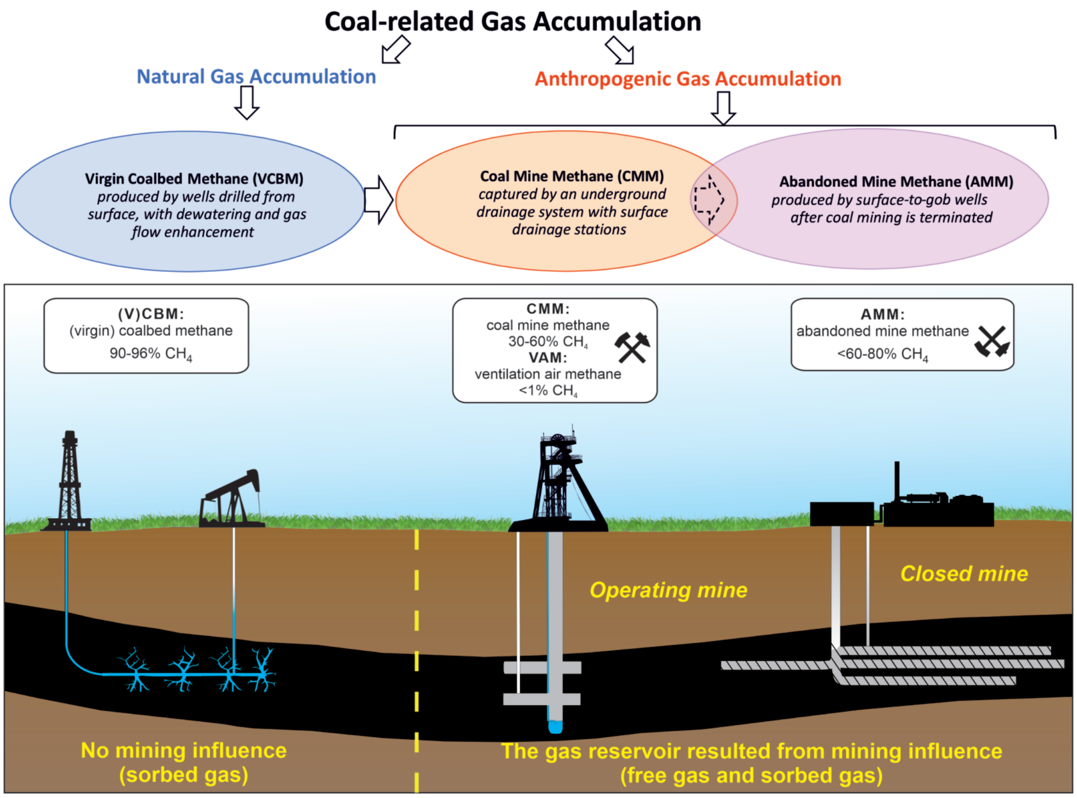

Fig. 1. Coal-related gas accumulations (after Hadro et al., 2024)

fields). However, developing AMM resources is beneficial because economic profits are always combined with environmental and safety benefits. This is especially true in the light of the recent European climate policy. Reducing methane emissions from abandoned coal mines is an important part of EU regulation which recently came into force, and thus AMM development should also be of special interest to the state administration. An understanding of factors contributing to the effective development of AMM resources is critical for the long-term planning of AMM utilization in the USCB.

Identification of the most important factors contributing to the effective development of AMM resources in the USCB has been made possible as a result of the AMM assessment study conducted by the Upper Silesian Branch of the PGI-NRI. The evaluation of AMM resources and reserves has been the core of that study, and we describe its results, followed by detailed discussion of the four groups of factors which make the greatest contribution to AMM development in the USCB.

AN OVERVIEW OF COAL GEOLOGY AND COAL-RELATED GAS RESOURCES IN THE USCB

The USCB is one of three Polish Variscan coal basins. It is filled with deposits of Upper Carboniferous age and is located in southern Poland, with 1/5 of the basin area located in the Czech Republic (Fig. 2). The Carboniferous basement comprises Precambrian, Cambrian and Devonian strata. The Carboniferous section begins with a carbonate association, passing into marine clastic deposits, and then into molasse coal-bearing strata (Mississippian and Pennsylvanian) which are divided into 4 main lithostratigraphic units, representing the time interval from Namurian A to Westphalian D (from Serpukhovian to Moscovian). The Carboniferous overburden consists mainly of Triassic, Miocene and Quaternary deposits, less frequently Permian and Jurassic, and in the southern part of the basin also the Carpathian overthrust (Upper Cretaceous and Paleogene) (Kotas, 1995; Jureczka et al., 2005).

A characteristic feature of the Carboniferous coal-bearing succession is its distinct bipartite nature. The older part of the coal-bearing section is formed of strata that originated in a paralic depositional environment, with a clearly visible influence of periodic marine ingressions (Gradziński et al., 2005), lithostratigraphically referred to as the Paralic Series (Namurian A – Serpukhovian). The younger strata of the coal-bearing sequence, developed in continental depositional environments, overlie the Paralic Series with a stratigraphic gap. Lithostratigraphically, the continental sedimentary section begins with the Upper Silesian Sandstone Series (Namurian A–C – Serpukhovian and Early Bashkirian) followed by the Mudstone Series (Westphalian A–B – Late Bashkirian and Early Moscovian), while the topmost formation is called the Cracow Sandstone Series (Westphalian B–D – Late Moscovian; Fig. 3). The present thickness of the Upper Carboniferous coal-bearing strata reaches a maximum of ~4,500 m in the western and central parts of the basin, and decreases towards the east to several hundred metres, partly due to the pinching out of certain lithostratigraphic units. The structural setting of the USCB was developed as a result of two orogenic cycles: the Variscan and the Alpine. During the Variscan orogeny, two zones of different tec-

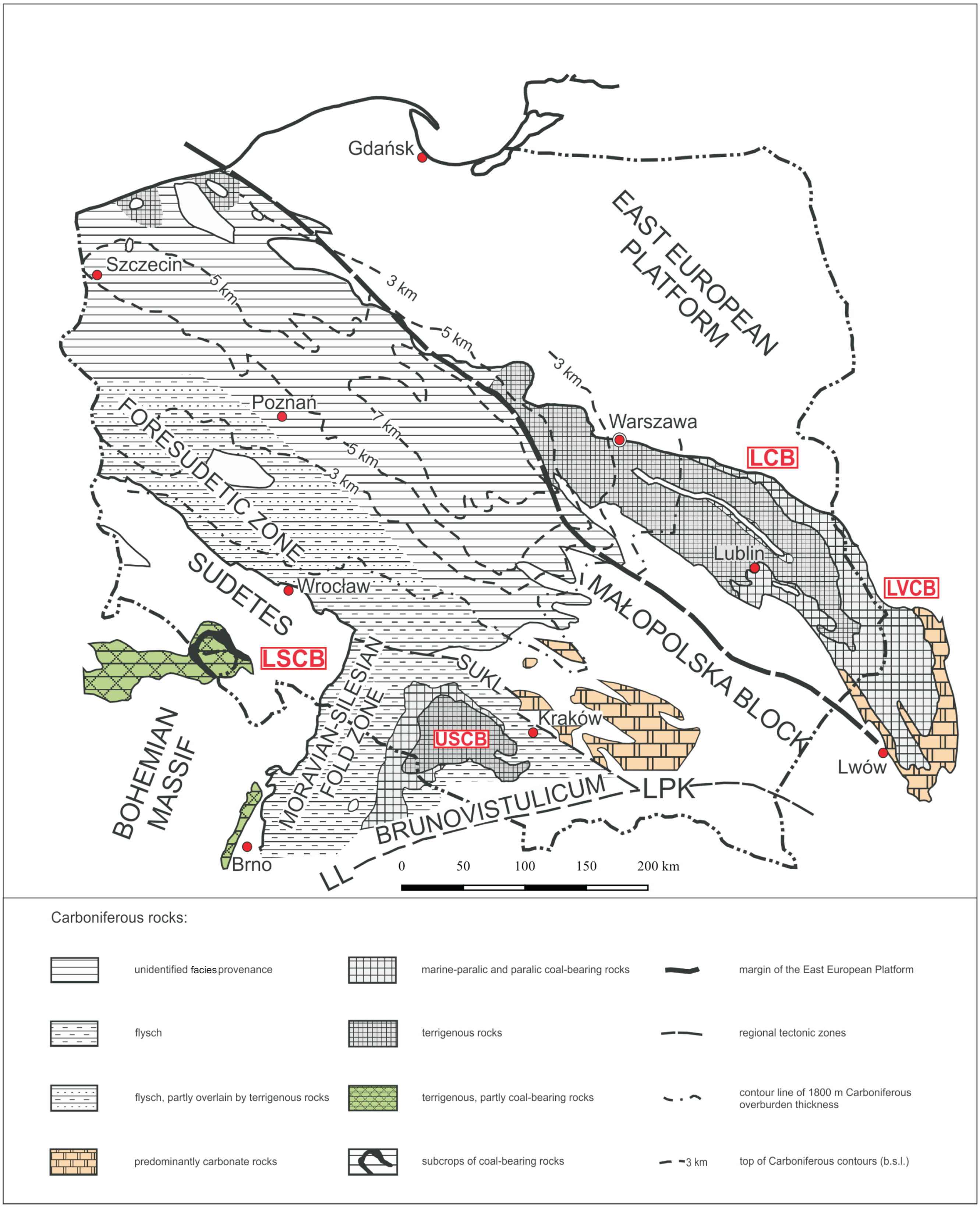

Fig. 2. Locations of the USCB and the other Variscan coal basins on a map of the Carboniferous facies distribution in Poland (after Kotas and Porzycki, 1984; modified Jureczka and Nowak, 2016)

LCB – Lublin Coal Basin, LL – Lednice line, LSB – Lower Silesian Basin, LVCB – Lviv-Volyn Coal Basin, PCL – Peri-Carpathian lineament, SUKL – Kraków-Lubliniec fault zone, USCB – Upper Silesian Coal Basin

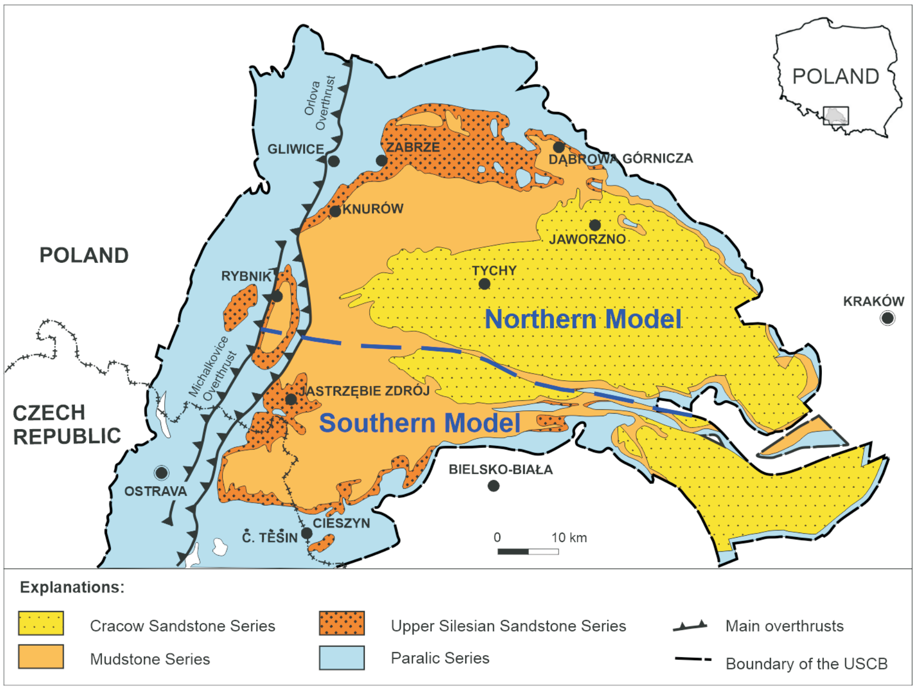

Fig. 3. The USCB – a subcrop geological map of the Carboniferous lithostratigraphic formations at the Carboniferous top surface (after Jureczka et al., 1995 – simplified)

tonic character were formed in the USCB: a fold tectonic zone and a fault tectonic zone (Kotas, 1972, 1985, 1995; Jureczka and Kotas, 1995).

The present-day distribution of coalbed methane content has developed as an interplay of geological, structural and hydrogeological factors, as well as of the complex thermal and erosional history of the USCB. Two patterns of methane content distribution in vertical section have been identified. They differ in their geological history and, due to their occurrence in different parts of the basin, they are referred to as the "northern" and "southern" models (Figs. 3 and 4; Kotas et al., 1994).

The "northern" model of coalbed methane content distribution is typical of the Carboniferous coal-bearing sequence with a thin, permeable overburden, which is outgassed to considerable depths of 500–800 m, and in some areas even <1000 m. The Carboniferous lithology is a key factor controlling the depth of outgassing which is defined as the configuration of the top surface of gassy coal seams. The depth of coal outgassing does not depend on the Carboniferous stratigraphy; however, in certain areas it is consistent with the position of some lithostratigraphic boundaries, e.g. the base of the Cracow Sandstone Series in the eastern part of the USCB. In the sequence of gassy coal seams, an increase in gas content values is usually observed to a depth of 1100–1300 m (Fig. 4). Apart from the areas located west of the Orlova overthrust, lithostratigraphically, the highest gas content values occur in the Załęże Beds (only in the lowermost part), the Ruda Beds and the Anticlinal Beds. In turn, the coal seams of the Libiąż and Łaziska Beds are practically completely outgassed (Hadro and Jureczka, 2020a).

The "southern" model is typical of the southern part of the USCB, where the Carboniferous sequence is covered by impermeable Miocene clay deposits. The Miocene seal was a main cause of the formation of the secondary zone of gassy coal seams at shallow depths, below the Carboniferous erosional top surface. These coal seams were resaturated with

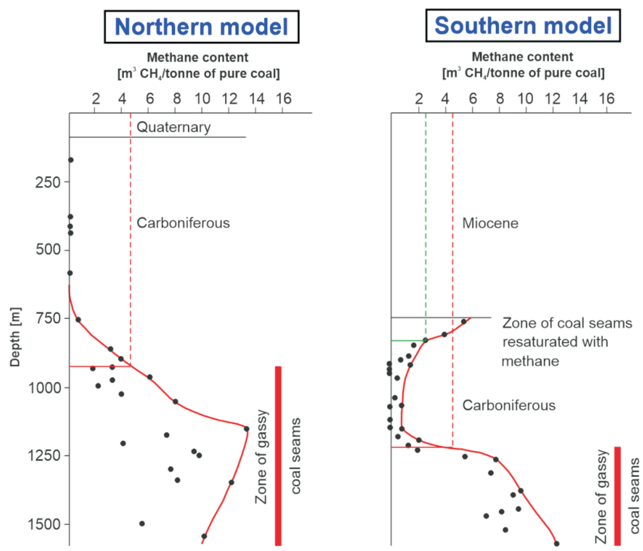

Fig. 4. Two patterns of coalbed methane content distribution in vertical section, referred to as the northern and southern models (after Kotas et al., 1994)

methane generated by bacteria or that had migrated from deeper gassy coal seams. Thus, the "southern" model features a vertical methane content distribution with two maxima: the first one represents a shallow, secondary zone of gassy coal seams (usually up to ~100–200 m below the Carboniferous top surface), the second one signifies a primary zone of gassy coal seams occurring at greater depths (Fig. 4). Similarly to the "northern" model, the depth to the top of the primary zone of gassy coal seams is not dependent on Carboniferous litho-

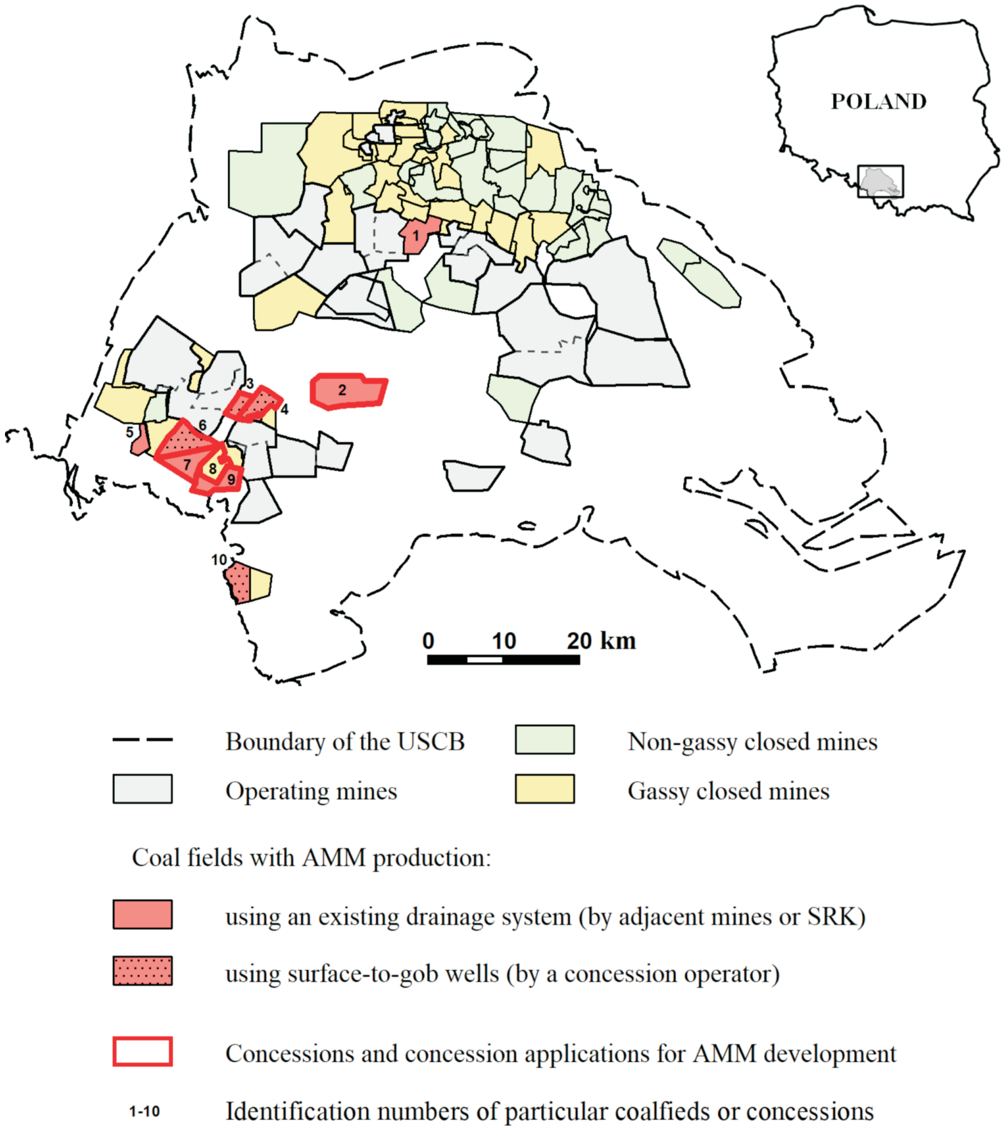

Fig. 5. Abandoned mines and operating mines as well as concession areas for AMM production in the USCB

Concession or concession application areas assigned to particular coalfields are denoted by numbers as follows: 1 – Śląsk, 2 – Krupiński, 3 – Jankowice Wschód, 4 – Żory 1, 5 – Anna (Czyżowice coalfield), 6 – Wilchwy, 7 – Mszana, 8 – Jas-Mos, 9 – Moszczenica, 10 – Kaczyce

stratigraphy. The gas content values of the primary zone increase with depth, reaching a maximum in the broad range of 1000–1400 m. There are deviations from the southern model pattern in certain areas where the primary and secondary zones of gassy coal seams are merged or the shallow gassy coal zone is absent (Hadro and Jureczka, 2020a).

AMM OCCURRENCE, DEVELOPMENT AND RESOURCES IN THE USCB

The historical peak of coal production in the USCB (almost 200 million tonnes) came in the late 1970s and the early 1980s, with around 70 operating mines. Since that time the number of operating mines has gradually decreased. Currently, there are 27 active mines and coal production is <50 million tonnes. Between 1980 and 2020 40 mines have been closed, most in the late 1990s and the early 2000s (Hadro et al., 2024).

AMM gas occurrence is obviously related to those mines which were gassy while active. The geographical distribution of abandoned coal mines, divided into gassy and non-gassy mines, is depicted in Figure 5. Geographically, all abandoned coal mines in the USCB can be grouped into northern and southern clusters (Fig. 5). The northern mines substantially outnumber the southern ones. Such a distribution of coal mines is largely controlled by the geological and structural features of the coal basin. Nearly half of the northern mines were gassy while active, whereas all but one southern mine were gassy. However, not all gassy mines contain post-mining methane gas in such quantities as to justify commercial gas production. This situation is reflected in the historical AMM production and the commercial development of AMM in the USCB.

So far, two methods of AMM recovery have been used in the USCB. The first one uses the existing methane drainage system (downhole boreholes and pipelines connected to the surface drainage station), while the second technology entails application of surface-to-gob wells.

AMM production using existing methane drainage systems is primarily conducted for safety concerns. It commonly lasts few years after a mine closure and is performed by a mine operator or a special company dedicated to mine closure – the Mine Restructuring Company (Polish acronym – SRK). This type of AMM production was carried out in the past (before 2010) by the operators of mines adjacent to those which were closed or were in the process of abandonment. The available records show that AMM production using this technology was conducted in four abandoned mines, lasting a few years and starting immediately after mine closure (Grzybek, 2017; Łukaszczyk, 2019). Recently, AMM development with the use of this same technology has been carried out by the SRK during the decommissioning process of the following gassy coal mines: Jas-Mos, Krupiński, Śląsk. The legal basis for this type of AMM recovery has been a concession for the exploitation of coal and coalbed methane as an "accompanying mineral". Additionally, the SRK is entitled to produce methane without a concession while the process of coal mine decommissioning is taking place (Hadro and Jureczka, 2020b). The summary statistics of AMM production using an existing methane drainage system is shown in Table 1.

AMM development projects using surface-to-gob wells have been conducted by small private companies in the USCB. The primary goal of these projects is a long term utilization of AMM on a commercial scale. The legal basis for this type of AMM recovery has been a production concession for coalbed methane as a "main mineral". So far, this type of AMM production has been carried out in three abandoned mines: Morcinek, Żory and 1 Maja (Table 2) with total annual production commonly between 1 and 5 million m^3. The historical data of AMM production using surface-to-gob wells are shown in Figure 6.

Seeing the number of gassy mines which have been closed so far, it may come as a surprise that only three of these mines have had AMM development projects. This has happened mainly because coal mines in the USCB, with a very few exceptions, are adjacent to one another (Fig. 5). Therefore, when a coal mine is closed, the gas released from coal seams in this mine can be captured by the ventilation and drainage system of an adjacent active mine or mines. This way, the methane hazard of the closed mine is reduced while its AMM gas is transferred, contributing to the CMM of an adjacent active mine (Hadro et al., 2024).

AMM has not been formally distinguished as a separate type of gas accumulation and belongs to the broad category of CBM in the Polish jurisdiction. Therefore, AMM resources do not exist in official statistics and they are undifferentiated from VCBM resources which are published in the Minerals Yearbook of Poland. The only way to track down AMM resources is by reviewing the geological reports of CBM fields which are mandatory for launching AMM development projects with the use of surface-to-gob wells.

AMM resource evaluation procedures should follow Polish regulations concerning petroleum deposit evaluation with special requirements for coalbed methane. Resource estimation procedures prescribed in these regulations are typically intended for VCBM without taking into consideration specific features of AMM resources. As a result, the estimation of AMM resources uses the same standard volumetric method and the same reservoir model as in the VCBM resource evaluation (Hadro et al., 2024).

So far, six geological reports of coalbed methane deposits, covering four abandoned mining areas, have been submitted with a view to launching AMM projects. The evaluation of AMM accumulations described in all these reports used the assumption that the extent of AMM reservoir rocks reaches far beyond the mining disturbed zone as if it was a VCBM reservoir (Hadro et al., 2024). At the same time, the reserves estimates given in these reports are based on a gas production forecast derived

Table 1

AMM production using an existing methane drainage system in the USCB

Closed mine name	Year of mine closure	AMM produced by an adjacent mine or SRK	Period of AMM production	Cumulative AMM production million m^3
1 Maja	2001	Marcel	2001–2006	14.4
Anna (Czyżowice coalfield)	1987	Anna	1987–1992	9.0
Żory	1996	Jankowice and Borynia	1997–2009	26.8
Moszczenica	2000	Jas-Mos	2000–2004	16.2
Jas-Mos	2019	SRK	2019–2023	44.0
Krupiński	2017	SRK	2017–2022	73.4
Śląsk	2017	SRK	2017–2019	1.7

Table 2

AMM production using surface-to-gob wells in the USCB

Closed mine name	Year of mine closure	Coal field name	Period of AMM production	Cumulative production million m^3
Morcinek	1998	Kaczyce I	2004–2023	22.4
Żory	1996	Żory-1 + Jankowice Wschód	2012-ongoing	43.7
1 Maja	2001	Wilchwy	2023-ongoing	4.1

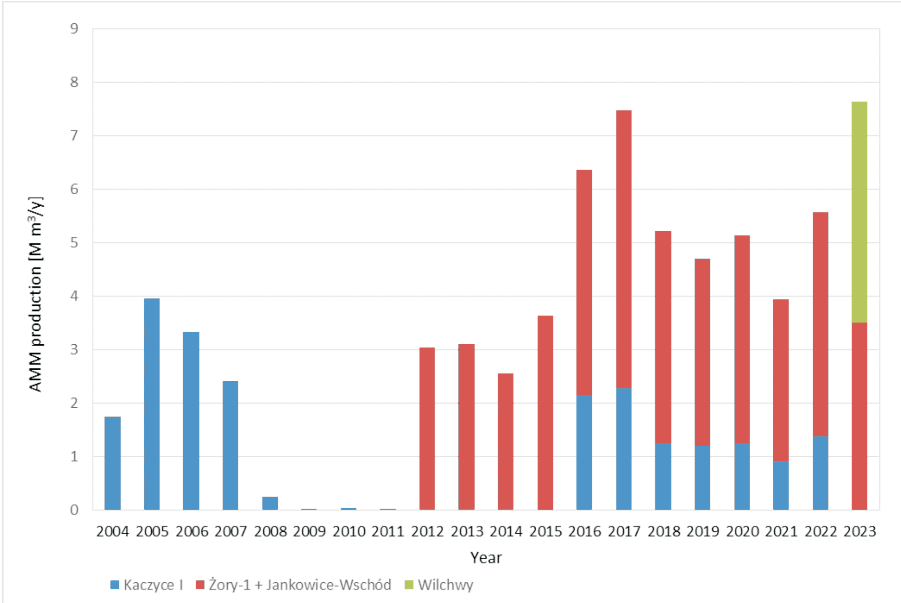

Fig. 6. AMM gas produced annually in the USCB from 2004 – colours represent AMM production concessions operated by private investors

from production test results. AMM resources and reserves reported by AMM concession operators or concession applicants are given in Table 3.

The molecular composition of gas from post-mining goafs (post-mining voids, often collapse-debris-filled) is highly variable and depends on many factors. At the end of mining, goaf gas, being a mixture of methane with ventilation air, contains commonly 40–60% methane (e.g., the Żory mine). Subsequently, after the mine ventilation is stopped, the methane content of goaf gas gradually increases depending on the local reservoir conditions (e.g., the degree of the goafs' isolation from operating mining areas). In the case of the Żory mine, due to the proximity of the operating mines (Borynia and Jankowice), the methane content in the goafs was in the range of 80–90% during the gas flow test conducted 13 years after the mine closure. The gas produced from the Żory mine is used for generating heat and electricity. Whereas, in the case of the Morcinek mine, which is an isolated mine, the goaf gas started to be produced within 6 years after the mine closure and contains 90–95% methane. Since it was high-methane gas, with gas composition remaining very stable for a long time (almost 20 years), it could have been capable of being transferred to the gas grid.

AMM RESOURCES AND RESERVES ASSESSMENT

To assess the AMM potential of the USCB, the Upper Silesian Branch of PGI-NRI was commissioned by the Polish government to conduct a research project entitled "Assessment of resource potential and feasibility of gas production from coal seams in the abandoned hard coal mining areas". After the multi-stage assessment of nearly 50 abandoned coal mining ar-

Table 3

AMM recoverable resources and reserves reported in the USCB

Closed mine name	Year of mine closure	Coalfield name	Estimated resources/reserves* [million m^3]	
			Recoverable resources	Reserves
Morcinek	1998	Kaczyce I	34.0	–
Żory	1996	Żory-1 + Jankowice Wschód	120.5	73.7
1 Maja	2001	Wilchwy	53.9	48.2
		Mszana	57.4	53.0
Anna	2012	Anna	139.2	40.9**

* – according to the Minerals Yearbook of Poland as of 31 December 2023 (Szuflicki et al., 2024); ** – according to the Geological and Investment Report of methane occurring in the Anna hard coal deposit as of 31 December 2020

eas, 11 of them were initially selected, while only 7 abandoned mining areas were considered prospective for a commercial AMM development in the USCB (Fig. 7).

In the first phase of the project, an attempt to estimate AMM recoverable resources using a standard volumetric method failed because the AMM reservoir boundaries cannot be unambiguously defined due to the presence of additional geological and structural factors. Therefore, the estimation of resources using a volumetric method was discontinued, and a new approach was proposed using a dynamic method, which gives approximate, but much more reliable results in the geological and mining conditions of the USCB (Hadro et al., 2024).

This new methodology of AMM resource estimation, which draws from the experience in forecasting methane emissions from closed mines in the United States, entails a total post-mining methane emission prognosis based on a hyperbolic decline curve against time (Coté et al., 2004; Franklin et al., 2004). The total methane emission at the end of coal mining is assumed as the starting point of a decline curve, and then the curve fit is calibrated using measured post-mining methane emission data. Assuming the lifespan of a future AMM production project (30 years), the initial reserves of the AMM are estimated (Hadro et al., 2024).

The new methodology for AMM resource estimation was used for the first time in the AMM assessment of the Krupiński closed mine, considered as a case study. The decline curve fit was applied for the 5-years post-mining emission rates from the starting point at the end of mining (Fig. 8). As a result, the total methane emission for the period of 30 years was estimated at 249 million m^3 (Hadro et al., 2024). However, the mine was planned to be flooded, so the post-mining emission prediction had to be adjusted for flooding, and this is considered as the final estimate of the initial AMM reserves, amounting to 139 million m^3. Taking into account the actual post-mining emission of methane by the year 2021 (79 million m^3), the remaining AMM reserves amount to 60 million m^3 (Fig. 8; Hadro et al., 2024).

The complete assessment of the Krupiński closed mine also included estimation of the initial coal-related gas volume (CMM and AMM combined) within the anthropogenic reservoir and the historical methane emissions developed with time. The total methane gas actually released while coal mining, which is referred to as CMM, was estimated at 1.9 billion m^3 (Fig. 9; Hadro et al., 2024).

Only ~1/3 of the CMM gas was captured and used, while the remaining gas volume was vented into the atmosphere. After coal mining was terminated, methane emission continued and was measured for 5 years during the process of mine closure. These data were used to predict the post-mining methane emission using a decline curve fit, and thus estimating the initial AMM reserves, while the remaining AMM reserves continuously change with time depending on the date from which the AMM production is planned to commence (Hadro et al., 2024).

As a result of multi-stage study of all gassy abandoned mines in the USCB, the newly developed methodology was used to estimate methane reserves for the seven abandoned mining areas considered prospective for AMM development.

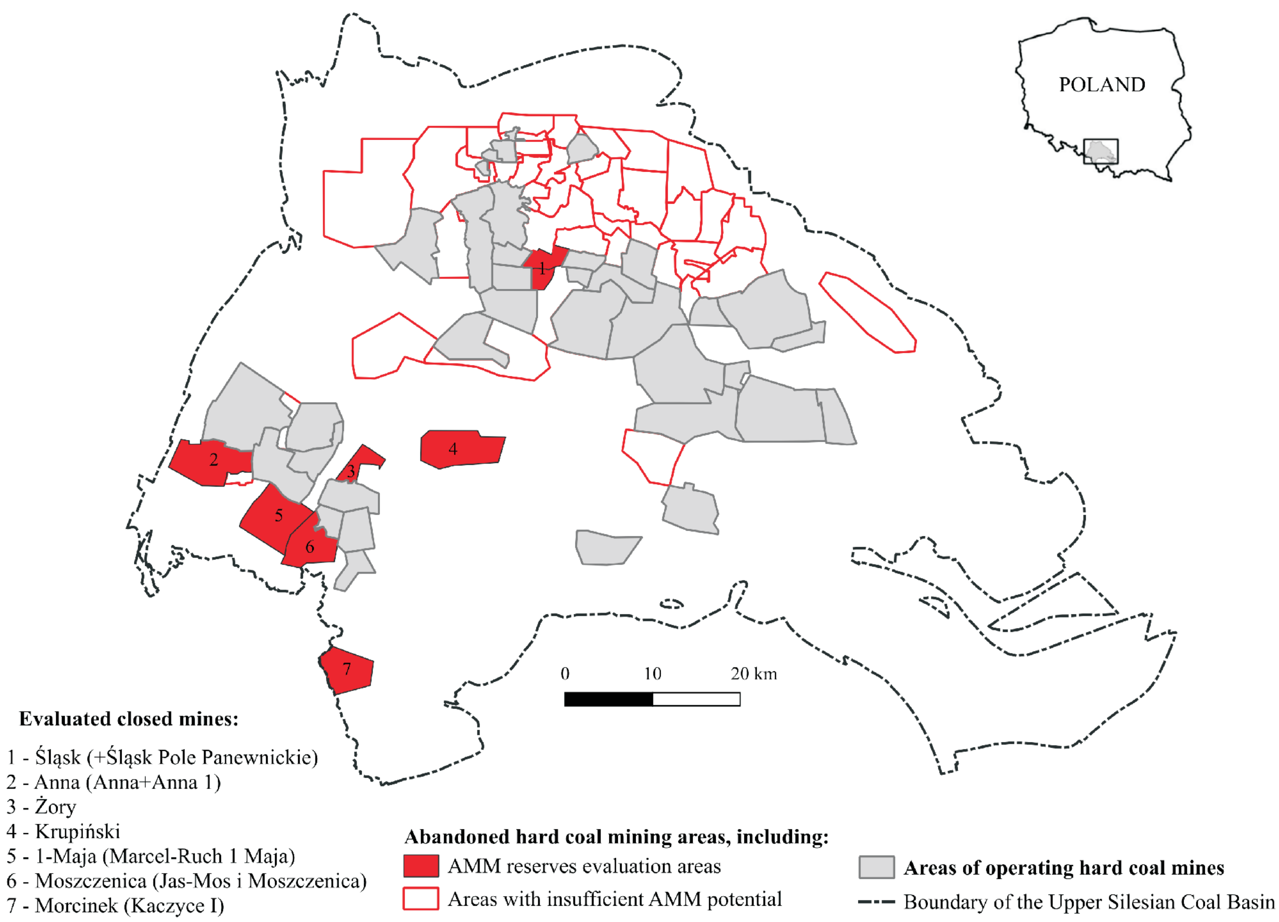

Fig. 7. Location of abandoned mining areas which are prospective for AMM development

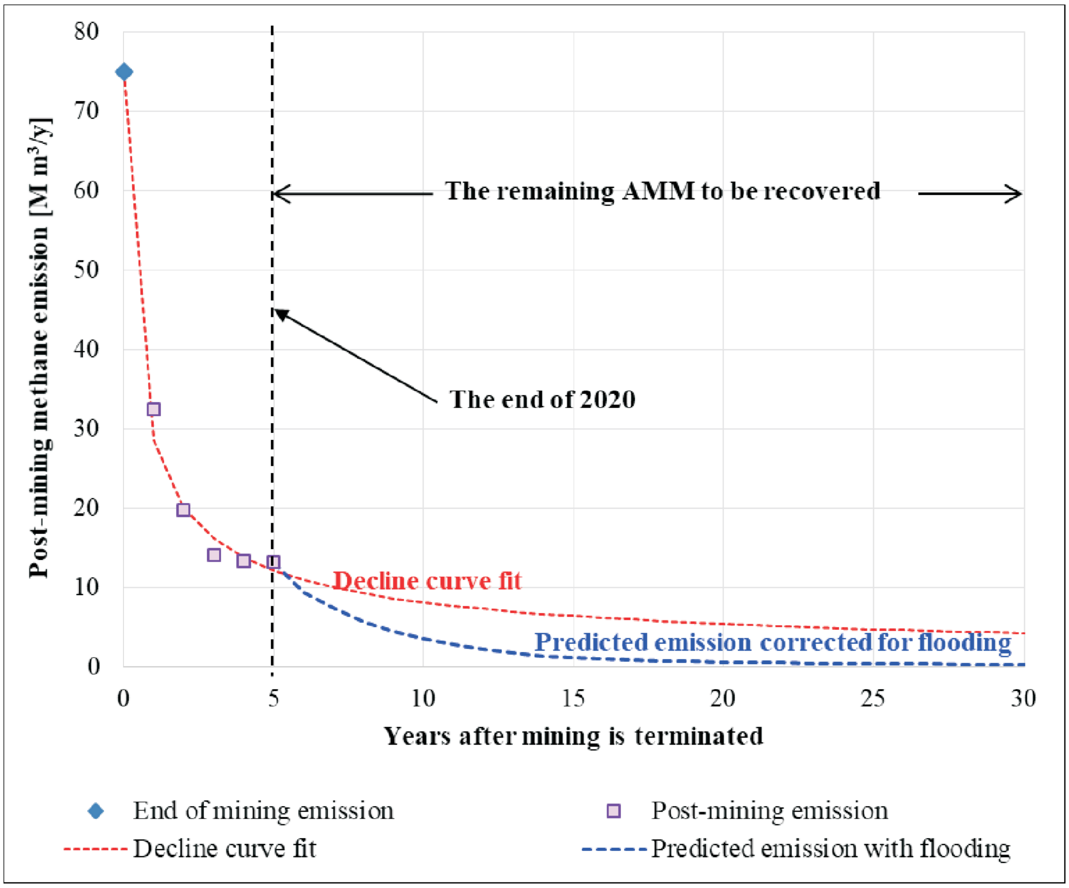

Fig. 8. Post-mining methane emission prediction for the Krupiński mine case study (Hadro et al., 2024)

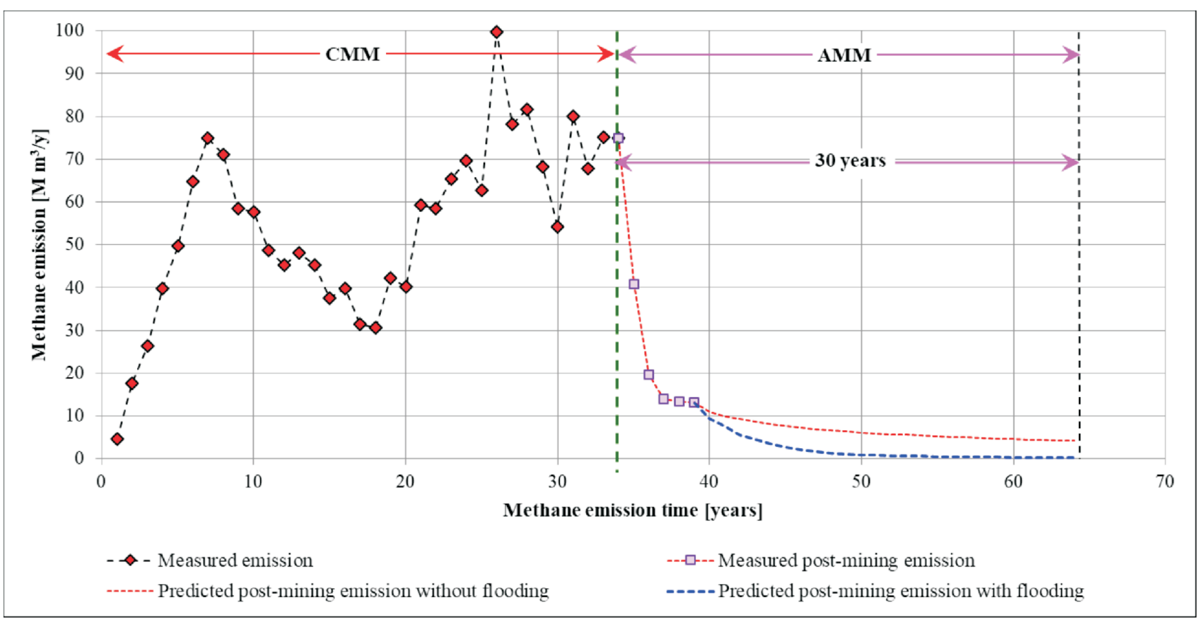

Fig. 9. Methane emissions during mining and post-mining emission prediction showing the total coal-related gas emission (CMM + AMM) from the anthropogenic gas reservoir of the Krupiński mine (Hadro et al., 2024)

The total initial AMM reserves of all the prospective areas amounted to 833 million m^3, of which 604 million m^3 had already been released prior to the date of estimation (31 December, 2020) indicating the total depleted AMM reserves (Table 4). The remaining AMM reserves of 229 million m^3 indicate future methane emissions available for capture and use from 2021 onwards (Table 4). According to available records, only 170 million m^3 of the past methane emissions were captured and used, while 426 million m^3 (i.e. 70%) of the AMM gas was not captured in a controlled manner, but migrated to the ventilation and methane drainage systems of the adjacent active mines and/or dispersed in the rock mass. This can be considered as the lost AMM gas potential which could have been captured and used (Hadro et al., 2024).

DISCUSSION

The detailed evaluation of these prospective abandoned coalfields, along with AMM resource estimates, allows us to distinguish and assess factors that favour the possibility of AMM commercial development in the USCB. Four groups of factors were considered the most important with regard to the effective recovery and utilization of AMM:
– geological and tectonic conditions,
– mining and technical conditions,
– AMM projects evaluation and resources/reserves estimation,
– regulatory issues.

GEOLOGICAL AND STRUCTURAL CONDITIONS

Methane emissions in gassy coal mines are primarily controlled by the permeability of the coal seams and surrounding rocks. The presence of low-permeability coal seams and the predominance of mudstone-claystone lithologies in the surrounding strata indicate that elevated permeability zones are usually well-correlated with coal mining areas of increased methane emissions, thus indicating mining areas potentially prospective for AMM development in the USCB.

Understanding of the geological and structural conditions, as well as the coal-related methane distribution in the USCB, along with the data analysis concerning methane emissions in gassy mines, enables us to distinguish two major factors responsible for the formation of the zones of increased permeability which are prospective for AMM development. The first of these factors is the presence of a secondary zone of gassy coal seams, occurring at shallow depths below the impermeable Miocene overburden (Kotas et al., 1994; Hadro and Jureczka, 2020a). Owing to its shallow depth (200–400 m), this zone has relatively high permeability compared to the permeability of the primary zone of gassy coal seams occurring at much greater depths (600–1200 m). Moreover, if the abandoned mine is flooded, the shallow gassy coal seams of the secondary methane accumulation zone remain above the level of rising water for a long time after the end of coal mining, which means that gas desorption from these coal seams continues, contributing to potential AMM production.

Considering the above, the best conditions for increased methane emissions from coal mines occur in the southwestern part of the USCB, where the "southern" model dominates in the vertical profile of methane content (Hadro and Jureczka, 2020a). In mines located in this part of the basin, this is reflected in the distribution of methane emission rates during the period of coal mining. The highest methane emissions occur in the initial phase of coal mining, and then slowly decrease (as in the cases of the 1 Maja and Moszczenica mines – Fig. 10, part A). The decrease in post-mining emission rates is also relatively slow for the mines located in the southern part of the basin.

By contrast, the distribution of methane emissions over time is entirely different for mines with a dominant "northern" methane content model, due to the presence of a deep interval of outgassed coal seams (Hadro and Jureczka, 2020a). Methane emission is low or non-existent at the early stages of coal mining, and rapidly increases at a later stage when mining is deep enough to reach gassy coal seams. Typically, there is a relatively rapid decrease in post-mining methane emissions due to the very low permeability of deep gassy coal seams, which is combined with flooding of the deepest mining levels (as in the case of the Śląsk mine – Fig. 10B). It is also possible to find an intermediate case when the secondary zone of shallow gassy coal seams occurs only in part of the mining area, and thus

Table 4

AMM reserves for the prospective abandoned mining areas of the USCB estimated using the new methodology (modified after Hadro et al., 2024)

Mine (coal deposit)	Mining period	Total CMM released	Initial AMM reserves	Total AMM released by 2020	Remaining AMM reserves
	from–to	MMm³			
Krupiński	1983–2017	1870	139.2	79.4	59.8
Śląsk (+Śląsk Pole Panewnickie)	1974–2017	488	19.1	5.1	14.0
Anna (Anna+Anna 1)	1955–2012	422	44.6	21.6	23.0
1 Maja (Marcel-Ruch 1 Maja)	1960–2000	2676	198.1	153.3	44.8
Moszczenica	1964–2000	3159	286.4	221.6	64.8
Morcinek (Kaczyce I)	1987–1998	195	76.3	62.7	13.6
Żory	1980–1996	259	68.8	58.9	9.0
Total		9070	832.5	**603.5**	**229.0**

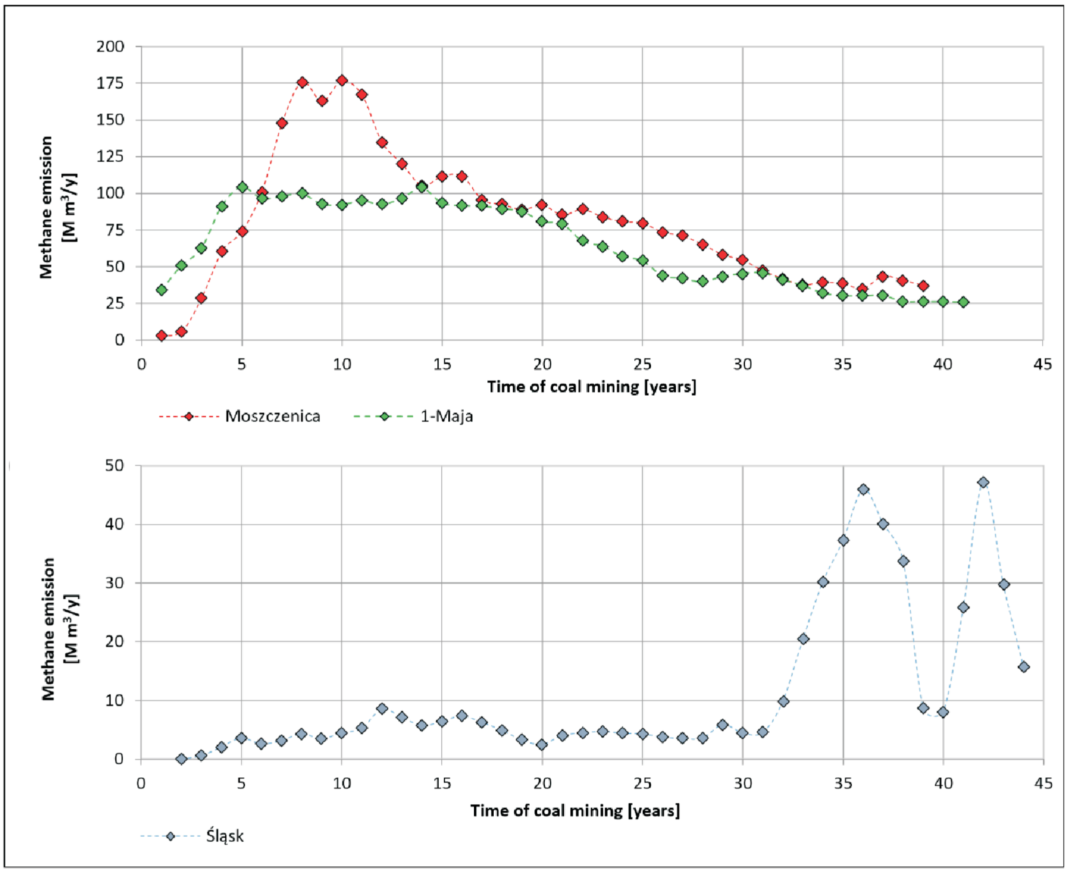

Fig. 10. Examples of methane emissions during coal mining: A – the 1 Maja and Moszczenica mines and B – the Śląsk mine

methane emission rates are more variable during the period of coal mining (for example, the Krupiński mine – Fig. 9).

A second factor clearly indicating an elevated AMM potential is the presence of faults, causing the formation of additional gas migration pathways in coal-bearing strata disturbed by mining. When a coal seam is mined, its overlying and underlying strata are relaxed, leading to the formation of a fracture network (a zone of relaxation) the extent of which can be enhanced by the occurrence of abundant tectonic deformation structures in the vicinity of mining areas. Thus, the zone of increased permeability that is thus formed has a much larger extent than the zone of relaxation which is theoretically estimated as a result of the methane emission prognosis. This effect is further magnified when the shallow, secondary zone of gassy coal seams is merged with the primary deeper gassy coal seams.

The best example of the formation of an extensive methane drainage zone, formed due to the existence of a tectonically enhanced fracture system, is the Krupiński closed mine, which was subjected to detailed analysis in the PGI-NRI project. In this mine, 17 isolated coal mine methane (CMM) reservoirs were distinguished, for which the original methane resources (in the zone of relaxation) were estimated and compared with the total volume of methane released as a result of coal mining. In the case of the vast majority of CMM reservoirs, the total volume of methane emissions exceeded the original methane resources estimated for the zone of relaxation. These excessive emissions were found to correlate with the presence of extensive faulting (Fig. 11). The metric of excessive methane emission is the ratio of the total volume of methane emission to the original methane resources in the zone of relaxation. In the southwestern part of this mine, where the density of the fault network is the highest, this ratio mostly ranges from 3 to 4, which is significantly higher than in the central-western and central-eastern parts of the mine, where it drops to 2 and 0.7 respectively.

MINING AND OPERATIONAL ISSUES

The effective use of AMM resources in the USCB, in addition to geological factors, depends on coal mining conditions including: mining methods, underground methane drainage, mine decommissioning procedures, as well as AMM capture technology. The issue of AMM development has not been systematically resolved so far. Historically, while planning the decommissioning of a gassy coal mine, attention was paid mainly to methane hazards, the elimination of which was most often possible by transferring post-mining methane emissions to an adjacent active mine owing to the existence of hydraulic connections between both mines. On the one hand, the capture of methane emissions from closed mines by neighbouring active mines is beneficial for safety reasons because it is an easy way of capturing AMM during the period of highest emission rates. On the other hand, this approach to AMM management contributes to masking the problem of AMM detrimental effects and undermines incentives for potential investors in AMM development projects.

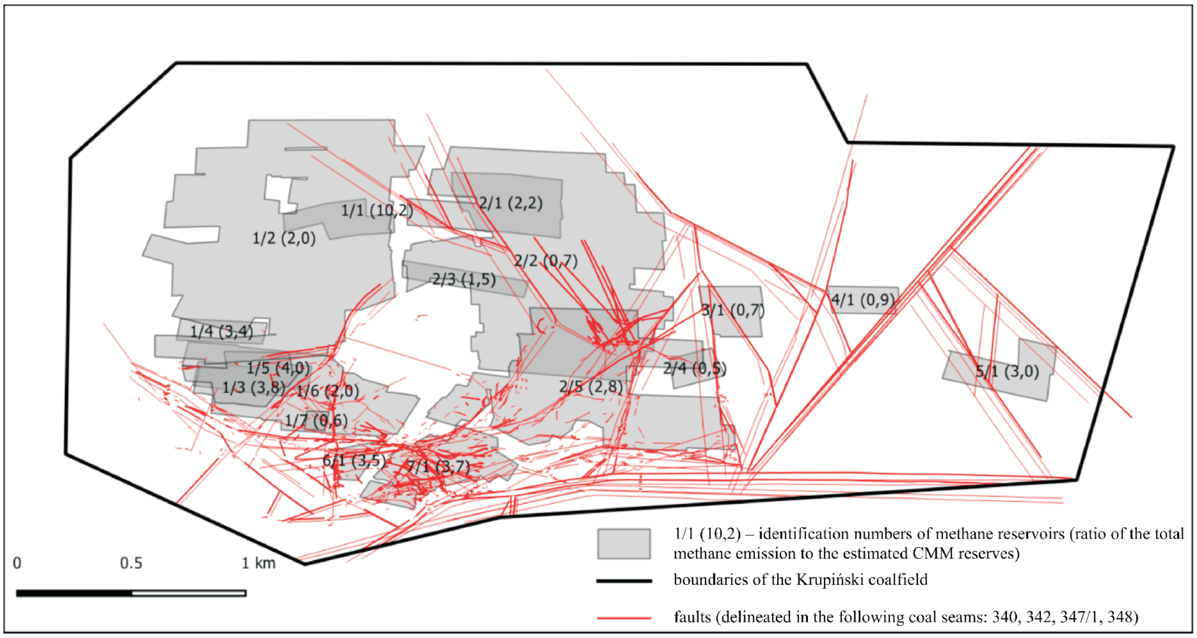

Fig. 11. Location of major faults identified in the closed Krupiński coal mine, as well as coal mine methane reservoirs defined by zones of relaxation

In recent years, methane released from post-mining goafs during the process of mine closure is usually captured by the existing methane drainage system operated by the SRK because the SRK becomes a mine operator while a coal mine is being decommissioned. Methane capture is then carried out for safety reasons, without a concession, until the process of mine closure is terminated. In any case, the methane recovery from closed mines using the existing methane drainage system, either by an active neighbouring mine or by SRK, has been conducted for safety reasons and is not an element of planned activities aimed at the development of AMM gas.

Surface-to-gob wells comprise the only AMM recovery technology which ensures the long-term capture and use of methane. Using this technology in Poland requires a concession for exploration and production of methane as a “main mineral”. Up to now, AMM has been produced using this technology by private investors in the USCB. This type of AMM development entails obtaining a concession, confirming the feasibility of AMM recovery and starting methane production using surface-to-gob wells. Remarkably, there has been a considerable time lag between the mine closure and the commencement of AMM projects. In the case of these three AMM projects that have been carried out in the USCB, for the Morcinek, Żory and 1 Maja closed mines, AMM production began 6, 16 and 22 years respectively after the cessation of coal mining (Table 2).

Considering the rapid decline in AMM gas flow rates immediately after coal mining is discontinued, uncertainty in the extent of a mining disturbed zone and gas migration pathways, the effective AMM development requires taking specific measures during mining operations, especially during the process of mine closure.

Planning for rational and effective AMM development should be done in advance, well before mine closure. While mining operations are still ongoing, the most important planning tasks include continuous monitoring of methane emissions, determining the extent of the relaxation zone and gas reservoirs, as well as estimating potential AMM resources. Also, it is important to assess the feasibility of using the existing underground methane drainage system for future AMM recovery. It is advisable that the implementation of the these AMM development planning activities should be somehow forced by the provisions of the Geological and Mining Law concerning mining operations and mine closing procedures, as well as by geological evaluation and the reporting system. Therefore, appropriate changes in the regulatory regime are recommended.

An extremely important factor influencing the management and results of AMM development is also whether mine dewatering is continued, which is usually the case in closed mines adjacent to active mines. If a gassy mine is flooded, there may be a certain time margin allowing for the production of AMM before the post-mining methane reservoir is filled with water, hindering gas desorption from coal within the zone disturbed by mining. This is of fundamental importance for assessing the feasibility of AMM projects.

AMM PROJECT EVALUATION AND RESERVES/RESOURCES ESTIMATION

The methodology of evaluating and estimating AMM resources is of paramount importance in the process of planning AMM development. The volume of estimated AMM resources and reserves is essential for the economic evaluation of AMM development projects, whereas the reliability of AMM reserves estimates and the accuracy of AMM production forecasts affect the risk assessment of AMM development projects (Creedy, 2019).

The development of AMM gas resources entails obtaining a hydrocarbon concession, i.e. a joint concession for exploration, appraisal and production of coalbed methane. A precondition for obtaining such a concession is to have the right to the geological and investment report of a hydrocarbon deposit, prepared in accordance with the applicable legal provisions in which recoverable resources and reserves are estimated. When applying for a concession, the investor’s intention is to develop AMM resources. However, according to the provisions of the Geological and Mining Law (GML), AMM is attributed to the category of a concession for exploration and production of VCBM in spite of the fact that an AMM accumulation, formed as a result of mining activities, is fundamentally different from naturally occurring VCBM. This difference is especially manifested in the technology of gas recovery. AMM gas is produced using surface-to-gob wells operated under vacuum, while VCBM is usually recovered using surface-to-in-seam horizontal wells with fracture stimulation (e.g., hydraulic fracturing) and continuous dewatering. Failure to take this difference into account in AMM evaluation reports leads to an inadequate gas field development model and to resource estimation errors.

The assessment of the geological reports approved to date, prepared with the intention of developing AMM gas accumulations, revealed a number of shortcomings in the current approach to evaluating and estimating AMM resources, which are summarized below:

• significant overestimation of recoverable resources due to incorrect determination of the reservoir boundaries – no definition of the extent of an AMM reservoir, which is considered to be equal with a VCBM reservoir;

• unreliable estimates of gas resources due to averaging methane content values obtained with the use of different measurement techniques applied at different stages of coal seam degassing induced by mining;

• unreliable estimates of gas reserves due to relying on production forecasts without taking into account the flow dynamics of gas remaining within the post-closure reservoir, and false assumptions related to the overestimation of recoverable resources available for commercial production.

Considering the above, effective AMM development requires modification of the current approach to evaluating and estimating AMM resources. The estimation of AMM resources is unique because it must take into account the continuous change of remaining gas resources over time, the dynamics of which depend mainly on the configuration of the post-mining methane reservoir and the depth of the formation water table, as well as the permeability of coal seams and surrounding rocks. The methodology for estimating AMM resources is therefore complex and should clearly differ from the oversimplified approach, derived from VCBM, which has been used in Poland so far. New rules for the evaluation of AMM accumulations should be developed, which will make this process more realistic and allow for the correct estimation of AMM recoverable resources and reserves.

The development of a new methodology for estimating AMM resources should be based on the results of this PGI-NRI project, which demonstrated the difficulties in determining the AMM reservoir model, especially where there is extensive structural deformation, and proposed the use of dynamic methods for estimating AMM reserves that take into account the flow dynamics of the gas remaining within the post-closure AMM reservoir. The approaches to estimating AMM resources in other countries should also be considered. Although the methodology for estimating AMM resources has not been standardized in international practice due to the complexity of the issue, there are a number of publications describing case studies of estimating AMM resources and reserves (Kershaw, 2005; Krause and Pokryszka, 2013; Collings et al., 2014; Karacan and Warwick, 2019; Creedy, 2019).

Another disadvantage of the current approach to estimating AMM resources is the fact that such estimates are basically limited to the official geological report of a gas deposit prepared for a concession application. As indicated above, AMM resources should be estimated before mine decommissioning procedures begin, regardless of estimating methane resources as an "accompanying mineral", which is usually part of the final resource assessment prepared as soon as the mining of a particular coalfield is terminated. The estimation of AMM recoverable resource should be based on a thorough analysis of methane emissions during coal mining and a reliable determination of the extent of post-mining gas reservoirs. Additionally, the AMM resource estimation should include preliminary gas production predictions (i.e. preliminary reserves) made on the basis of possible variants considered for the AMM field development.

REGULATORY ISSUES

Although methane utilization provides multiple economic and environmental benefits, AMM projects often face several implementation challenges. The regulatory regime governing AMM production and utilization can play an important role in overcoming technical and market barriers. It can also be useful in developing incentives or tax policies to promote AMM utilization.

In Poland AMM evaluation procedures have to be performed in compliance with the GML which divides coal-related gas accumulations into two basic types. The first type is a methane gas accumulation classified as a "main mineral", which is applicable to virgin coalbed methane (VCBM) and follows a petroleum resource regulatory regime. The second type is a methane gas accumulation classified as an "accompanying mineral", which is applicable to coal mine methane (CMM) and follows a coal resource regulatory regime. Although AMM is an anthropogenic gas accumulation, which emerged from CMM, it has been officially classified to the first type of methane gas accumulation and is treated on the same grounds as VCBM, with far-reaching consequences. Thus, the most important repercussion is a legal obligation to evaluate AMM resources as per the regulation concerning reporting of petroleum deposits, which entails two major consequences. Firstly, resource estimation procedures prescribed by this regulation are typically intended for VCBM resources and do not take into consideration specific features of AMM, leading to serious estimation errors as described above. Secondly, concession activities conducted under the petroleum resource regulatory regime are costly and time-consuming, which is discouraging to private investors and causes substantial delays in AMM development (Hadro and Jureczka, 2020b).

In view of the above, the provisions of the GML should be modified to allow for appropriate changes in the methods of AMM resources evaluation. Since an AMM gas accumulation is of anthropogenic origin, the source rock of which is coal, AMM should be differentiated from both VCBM and conventional gas. On this basis, a concession for exploration and production of AMM accumulations should be excluded from petroleum type jurisdiction, and then the concession procedures should be simplified and streamlined. This purpose should be served by unifying the terminology used in the evaluation process of coal-related gas resources in such a way as to draw a clear distinction between AMM and CMM or VCBM.

New circumstances that start to play a significant role and may have a considerable impact on AMM development appeared together with the Regulation of the European Parliament and of the Council on methane emissions reduction in the energy sector (EU 2024/1787), which came into force on August 4, 2024 [Regulation (EU) 2024/1787]. The methane emissions reduction provisions for underground coal mines covers all operating mines as well as closed and abandoned mines. The regulation also provides for a strict package of sanctions in the event of non-compliance with its provisions. With regard to methane emissions from closed and abandoned underground mines, the most important requirements of the Regulation (EU) 2024/1787 are as follows:

• within 1 year – setting up an inventory of all closed and abandoned coal mines where operations have ceased within the last 70 years; the inventory shall contain, among other information, the results of methane concentration measurements at all emission sources;

• within 21 months – installation of measuring equipment on all identified emission sources exceeding 0.5 tonnes of methane per year;

• within 3 years – development and implementation of a mitigation plan to address methane emissions from closed and abandoned coal mines, which is submitted to the competent authorities;

• after 1 January 2030 – prohibition on methane emissions to the atmosphere and flaring of methane from closed and abandoned coal mines (with certain derogations).

Although the new EU regulation is considered burdensome and a challenge for the Polish government, it is overall beneficial to AMM development in the USCB. All these requirements concerning emission reduction in closed and abandoned mines will put a considerable pressure on the government to reduce methane emission in closed mines. AMM development is one of the most obvious ways to achieve this objective. Therefore, the government should introduce the necessary legal changes in order to simplify the process of granting concessions for AMM development and to improve AMM resource/reserves evaluation procedures as discussed earlier. Also, in setting stringent requirements concerning methane emission monitoring, the new EU regulation may be useful in identifying areas of closed and abandoned mines with a high potential for AMM development.

CONCLUSIONS

The Upper Silesian Branch of PGI-NRI conducted a comprehensive research project to evaluate AMM resources in the USCB. A newly developed methodology was used to estimate the initial and remaining AMM reserves of seven abandoned coal mines considered prospective for AMM development. The AMM reserves estimation results indicated that the recovery and utilization of AMM is poorly developed in the USCB. Only three commercial AMM development projects have been implemented so far, with a significant time lag (from 6 to 22 years) in starting the project after the end of coal mining.

Based on the PGI-NRI project findings, the most important factors contributing to the effective development of AMM in the USCB, identified and discussed in this paper, are as follows:

1. Geological and structural conditions are related to two major factors. The first one is the presence of a shallow zone of gassy coal seams resaturated with methane, occurring in the southwestern part of the USCB. The second factor is the presence of numerous tectonic features (mainly faults) that propagate extensive networks of mining-induced fractures, forming an increasingly large AMM reservoir with multiple gas migration pathways.

2. Mining and technical conditions include planning AMM recovery well in advance, while the mine is still in operation and during the process of mine closure. The most important activities in this area include monitoring methane emissions from longwalls, determining the extent of the AMM gas reservoir, estimating AMM resources and possibly adapting the existing underground methane drainage system to the conditions of future AMM projects.

3. AMM project evaluation and reserves/resources estimation is important for assessing the feasibility of AMM development. Estimating recoverable resources is difficult due to the uncertainty in determining the boundaries of AMM reservoir rocks. Nevertheless, initial AMM reserves can be approximately estimated using a post-mining emission decline curve, assuming a 30-year period of AMM production. The decline curve can be continuously calibrated with the amount of actual methane emissions or production. Given the complexity of AMM resource estimates, special attention should be paid to the development of an appropriate estimation methodology.

4. Regulatory issues entail modifying existing legal provisions that hinder the development of AMM resources. Recommended changes include separating AMM from VCBM and exempting AMM from petroleum jurisdiction, along with simplifying licensing procedures, as well as modifying provisions on the evaluation and estimation of AMM resources. An important factor of legislative nature is the recently introduced EU Regulation on the reduction of methane emissions in the energy sector, which entails monitoring and mitigating methane emissions from closed and abandoned mines. The development of AMM resources is one of the most obvious ways to reduce methane emissions from closed and abandoned mines. The introduction of the EU Regulation requirements should provide support for AMM projects through the synergy effect, and will also exert additional pressure to quickly and effectively implement all previously recommended changes postulated in this article.

The first group of these factors refers to the understanding of the basin geology and structural setting, which is based on the plethora of geological data acquired during the long process of coal exploration and mining in the USCB. The remaining three groups of factors are related to breaking down existing barriers that have common roots in the legal and administrative system, change in which is crucial to the effective and rational management of AMM resources in the USCB.

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