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ORIGINAL ARTICLE

Methane emissions against the background of natural and mining conditions in the Budryk and Pniówek mines in the Upper Silesian Coal Basin (Poland)

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Abstract
The paper presents the variability of hard coal output, methane content and methane emissions into coal workings and into the atmosphere from the two most methane-gassy coal mines in Poland. The Budryk mine is one of the youngest mines in Poland, but it is the most methane-gassy as well. In 2016, the total CH_4 emissions exceed 140 million of m^3. This large increase in methane emissions to mine workings is primarily related to the increase in the depth of coal extraction (up to 1290 m) and, consequently, the rapid increase in the methane content in coal seams (up to 10–12 m^3/Mg coal^{daf}). On the other hand, in the Pniówek mine, methane emission was the highest at the beginning of the study period (1986–1991). During the following years, emission decreased to the values of less than 140 million of m^3, which were still one of the largest amounts of emitted methane in the entire Upper Silesian Coal Basin. The coexistence of natural factors, such as the geological structure and gas distribution, as well as mining-related factors, i.e. the depth of mining, the intensity of coal extraction determines the temporal variability of methane emissions in the studied mines.

Keywords Methane emissions · The Upper Silesian Coal Basin · Budryk mine · Pniówek mine · Hard coal output

Introduction

The Upper Silesian Coal Basin (USCB) (Fig. 1) is the most industrialised region in Poland, providing bituminous coal for heat and power generation, as well as coking coal for coke production. Reaching deeper deposited coal seams carries a high methane risk, a risk of underground tremors, and intensification of temperature hazards. The increase of methane emission is one of the most dangerous problems in modern mining activity and entails work suspension, evacuations and even fatalities after methane explosions (Trenczek 2016; Duda and Krzemień 2018; Dreger and Kędzior 2019). Two mines from the USCB, Budryk and Pniówek—members of the Jastrzębska Spółka Węglowa SA, were chosen to identify and study variations in methane emissions. These two mines are characterised by the highest CH_4 emission in the entire coal basin in Poland. Methane emissions to coal workings in the studied mines are often more than 100% higher than in other mines in the basin (GIG 1995–2019). The total methane emission in the USCB has been changing with time. In 2004, methane emission from all mines amounted to more than 800 million m^3 and in 2015 exceeded 900 million m^3. The entire emission values fluctuated from year to year, but the overall emission trend is increasing. A similar trend was observed in other coal basins, where coal was extracted from deeper levels every year e.g. (Ju et al. 2016; Wang et al. 2019; Karacan and Warwick 2019). On the other hand, the hard coal output in Poland has been constantly decreasing from over 100 million Mg at the end of the twentieth century to around 60 million Mg in 2016–2018. Methane (CH_4) is the second-most important greenhouse gas after the notorious carbon dioxide (CO_2) and plays a potent role in atmospheric chemistry and radiation balance (Warmuziński 2008; Ghosh et al. 2015; Kędzior 2015; Tutak and Brodny 2019; Swolkień 2020; Dreger 2021).

The amount of methane emission from a coal deposit is strictly dependent on many factors, which can be roughly divided into natural factors related to the geological structure

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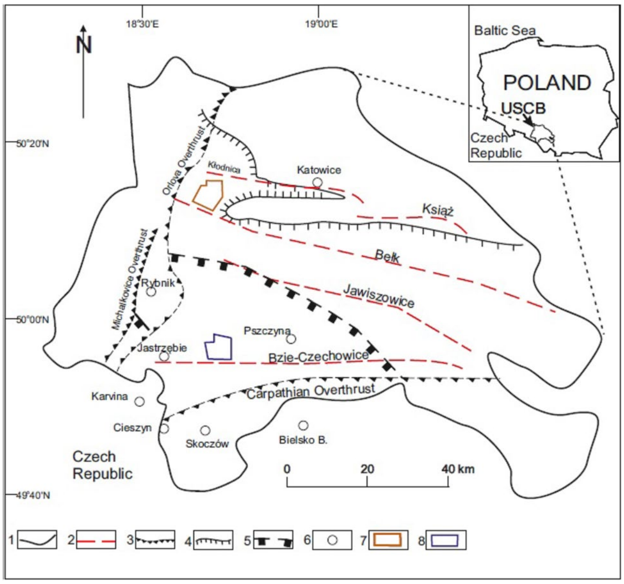


Fig. 1 Map of the Upper Silesian Coal Basin (modified after Kędzior 2012) 1—the boundaries of the Polish part of the USCB, 2—important fault zones, 3—overthrusts, 4—the range of the continuous Miocene cover, 5—the range of the secondary methane zone (ticks point the direction inside the areas of ranges), 6—important cities, 7—the Budryk mine boundary, 8—the Pniówek mine boundary

of the deposit and its natural gas content and pressure, as well as anthropogenic causes resulting from mining activities and the method of deposit exploitation e.g. (Karacan et al. 2011; Krause and Smoliński 2013; Kędzior and Dreger 2019; Dreger 2020). Therefore, the interrelationship of available results regarding the gas content of the deposit, volume and intensity of coal extraction with the data on the quantity of methane emissions should make us aware of how strongly the described factors affect the phenomenon of emissions and, therefore, how to counteract it.

Accordingly, the main purpose of this article is to show how the dependencies and causes of methane emission and hard coal output have changed with time (1986–2018) in the two most methane-gassy coal mines in Poland. The Pniówek coal mine is characterised by the one of the highest methane emissions in Poland. In the Budryk mine, methane emission has been increasing rapidly since 2013 and now it is the highest in the country.

Data sources

All the data were obtained from officially accepted geological documentation from the Budryk and Pniówek mines belonging to the Jastrzębska Spółka Węglowa SA (JSW—internal reports). In addition data from the Annual Report (for the years 1994–2018) on the state of basic natural and technical hazards in the hard coal mining industry published by the Central Mining Institute (GIG) in Katowice (GIG 1995–2019) were taken for calculations and analyses.

The most important data taken into research are the methane emission from two selected underground coal mines—Budryk and Pniówek. The total methane emission (CMM—coal mine methane) refers to methane liberated from the coal and surrounding rock strata due to mining activities. It is a combination of ventilation air methane (VAM) and methane coming from coal seam drainage (degassing). Ventilation air methane and degassing were also studied for these two coal mines. The VAM is commonly determined by measuring the pure methane concentration in the air stream by handheld anemometer and by taking air samples to the laboratory tests. The air velocity measurements are important to determine the methane concentration in the return airways (e.g. Karacan et al. 2011; Gawlik and Grzybek 2002). The specific CH_4 emission was investigated as well. This feature describes how many methane is emitted to the mining atmosphere with every extracted Mg of coal and it shows the real methane danger during mining activities. To measure the amount of adsorbed CH_4 in coal, we use the term methane content, which describes the volume of gas in one Mg of coal^{daf} (daf is the pure coal substance, without moisture and ash, dry ash free coal substance) (Wierzbicki and Skoczylas 2014; Honysz 2015).

Moreover, to study relations between methane content and coal seam pressure (methane desorption), the data collected by Tarnowski (1971) and CLP-B Sp. z o.o. Laboratory in Jastrzębie-Zdrój were also considered and carefully analysed. After the analysis of all collected data, the multi-criteria geology and mining evaluation were set up.

Coal mines under study

Budryk mine

The Budryk coal deposit is located in the northern part of the basin (Fig. 1) at the north-western flank of the Main Trough between two dislocations: the Kłodnica Fault in the north and the Bełk Fault in the south. The Budryk deposit is composed of 43 documented coal seams (from 325 to 407/3), all of which are found in the Orzesze, Załęże and Ruda beds. The deposit has a diverse geological structure, sediment disorders, and large tectonic variability (Table 1, Fig. 2). Carboniferous top surface varies in depth from + 60 m in the north to + 300 m above sea level in the south-east. The dip of the beds is varied, from almost horizontal to incline at 15° angle.

The largest dislocations in the USCB, such as the Kłodnica, Książ or Bełk faults, have nearly latitudinal orientation and displace layers to the south (Kędzior et al. 2013; Dreger and Kędzior 2019).

Table 1 Characteristics of the main faults in the Budryk and Pniówek mining areas (JSW internal reports)

	Budryk	Pniówek
Latitudinal direction		
Name/throw size/throw direction	Dębieńsko/25–45 m/N	Krzyżowice I/20 m/NW
	Barbara Fault Zone/30–55 m/S	Krzyżowice II/25 m/NW
	North/25 m/N	Pniówek/3–25 m/S
	Knurów/30–100 m/ SE	Skrzeczkowice/70 m/NNE
	Paniowy/25–26 m/SE	P-1[a]/15–22 m/S
	Śmiłowice/15–65 m/NW	
	Barbara I/30 m/SE	
	Paniówki/8.5–20 m/SW	
Longitudinal direction		
Name/throw size/throw direction	Chudecki/0.7–20 m/W	Pawłowice I/40–80 m/W
		Pawłowice II/60–100 m/W
		Warszowice/4–60 m/E
		Graniczny I/10–100 m/NE
		Graniczny II/10–30 m/NW
		Graniczny III/20 m/NE
		P-2, W-2[b]/5–20 m/E

[a]Unnamed fault which divides part of the P-1 deposit in the north and south

[b]Unnamed faults which divide part of the P-2 and W-2 deposits in the east and west

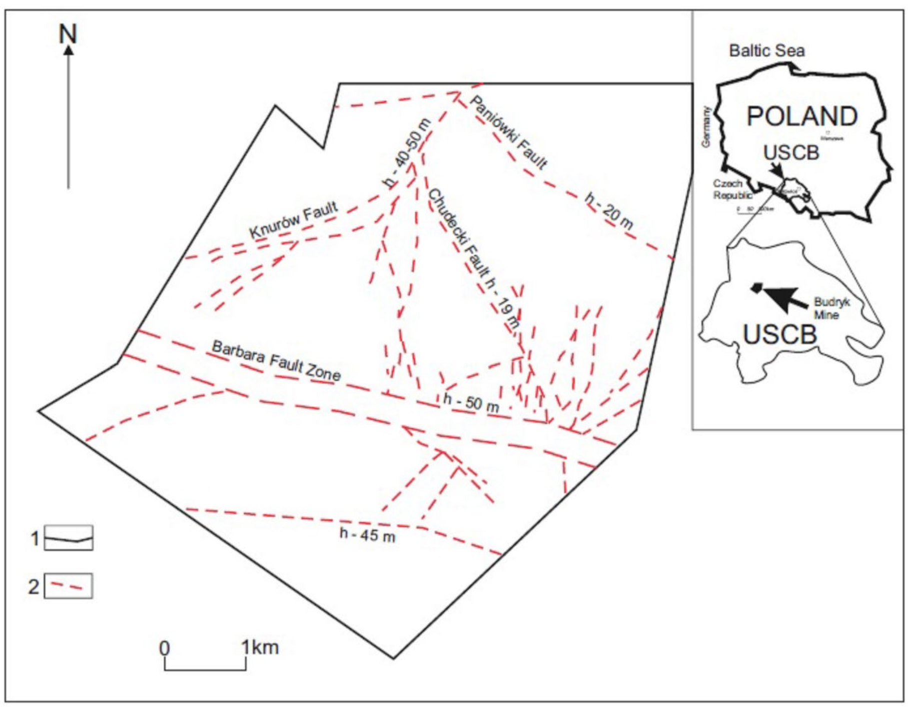


Fig. 2 Tectonic sketch of the Budryk Mine (402 coal seam), 1—the boundaries of the mining field of the Budryk mine, 2—faults with throw size h,

The Budryk mining area is represented by the Pennsylvanian Upper Silesian Sandstone Series (Namurian C; Serpukhovian and Bashkirian) and the Mudstone Series (Westphalian A and B; Bashkirian) (Table 2). In the profile of documented coal deposit Ruda (Namurian C; Bashkirian), Orzesze and Załęże (Westphalian B; Bashkirian) Beds were found.

The Upper Silesian Sandstone Series is represented by Ruda Beds occurring below the 407 seam where coarse and fine-grained sandstones were found. The following Załęże and Orzesze Beds (Westphalian A and B; Bashkirian) occur in all of the area with 800–1250 m thickness in total. They constitute the main stratigraphic unit in the deposit, built of mudstones, claystones and

Table 2 Upper Silesian Coal Basin stratigraphic division—modified after Heckel (2004) and Gabzdyl and Gorol (2008), C—carboniferous, M—Mississippian, P—Pennsylvanian

Stratigraphic division					Lithostratigraphic series	Layers
International (after 2004)			Local (modified after 2008)			
C	P	KASIMOV	STEPHANIAN	B	Kwaczała Arkose	
				A	Stratigraphic Gap	
		MOSCOVIAN	WESTPHALIAN	D	Cracow Sandstone Series	Libiąż
				C		Łaziska
		BASHKIRIAN		B	Mudstone Series	Orzesze
				A		Załęże
			NAMURIAN	C	Upper Silesian Sandstone Series	Ruda
				B		Saddle
				A	Paralic Series	Poruba
						Jaklovec
	M	SERPUKHOVIAN				Hrusov
						Pietrkovice
					Diastrophic sea deposits (flysch type)	Kyjovice (upper)
		VISEAN	UPPER VISEAN			Kyjovice (lower)

sandstones, with numerous coal seams which are the subject of mining.

Most of the Orzesze strata and the entire Carboniferous younger series (Cracow Sandstone Series) were removed by erosion in the mine area under study.

The overburden rocks lie discordantly on the Carboniferous erosion surface and consist of Triassic sandstones and carbonates, Miocene clays, as well as fluvial and glacial sediments of Quaternary origin. The total thickness of the overburden strata does not exceed 200 m (Table 3).

Pniówek mine

The Pniówek coal deposit is located in the south-western part of the USCB (Fig. 1) at the SW limb of the Main Trough, bordering with the Bzie-Czechowice fault zone in

Table 3 Overburden composition in the Budryk and Pniówek mining areas (JSW—internal reports; Kotas 1982; Buła and Kotas 1994)

	Budryk mine	Pniówek mine
Overburden	Quaternary, Neogene, Triassic	Quaternary, Neogene
Thickness	0–180 m	220–1000 m
Quaternary		
Thickness	0–79 m	6–80 m
Composition (lithology)	Sands, clays, gravels	Clays, sands, gravels
Description	Pleistocene glacier-water accumulation. Reduction in thickness in the S part of the coal deposit. In the SW part of the area deposits rest directly on the Carboniferous layer	Holocene alluvial and Pleistocene glacier-water and glacier accumulation
Neogene (Miocene)		
Thickness	< 134.8 m	150–900 m
Composition (lithology)	Clay, marl clay, marls, claystones, sand clays, sands, and sandstones	Marl, clay, sands, tuffites, sandstones, conglomerates
Description	Sediments found in the N, NE, W part of the mining area. Deposits lying on the weathered Carboniferous sediments and covered by Quaternary layers	Thickness is variable, with the thickest sediments in SE and the thinnest in N and W
Triassic		
Thickness	< 65.8 m	–
Composition	Clay and limestones marls, sandstones	–
Other	Sediments deposited directly on the Carboniferous layers. The biggest spread of sediments is found in the E part of the area	–

the south. The Pniówek coal deposit is a multilayer structure consisting of 62 documented seams of various thicknesses and qualities of the beds. Tectonic character of the deposit is also very complex, with fault throws between 10 and 300 m (Table 1, Fig. 3). Furthermore, we can distinguish many smaller faults accompanying larger dislocations throwing down the layers by a few metres.

The lithological profile of the Carboniferous strata within the discussed mine comprises the Pennsylvanian Paralic (Namurian A; Serpukhovian, Bashkirian), Upper Silesian Sandstone (Namurian B and C, Bashkirian), and Mudstone (Westphalian A and B; Bashkirian) Series.

All the Upper Carboniferous series are represented by clastic rocks, i.e. sandstones, mudstones and claystones in various quantitative proportions with numerous coal seams.

The Carboniferous top surface displays an erosive character and is morphologically varied. There are many paleo-ridges and washouts with a general NW orientation. There are clay and sandy Miocene deposits on the eroded Carboniferous surface. Their thickness is variable and ranges from about 200 m in the north to 1000 m in the south (Table 3).

Results and discussion

Methane distribution

Budryk mine

Current spatial distribution of the methane content in the Upper Silesian Coal Basin depends inter alia on the geological development of the basin in the past, the sorption capacity of the coal seams, the thick and hermetic Miocene overburden (methane accumulation), lithological character of Carboniferous sediments, and tectonic dislocations (methane migration) (Kozłowski and Grębski 1982; Kotas 1994; Kędzior 2009a, 2019; Słoczyński and Drozd 2018; Krause 2019) (Figs. 2, 3). In the Upper Silesian Coal Basin, two main geological patterns of vertical distribution of coal-bed methane (CBM) were distinguished (Kotas 1994; Kędzior 2009a) (Fig. 4). Pattern A is associated with northern and central areas of the coal basin, characterised by the presence of naturally degassed coal seams down to the depth of 400–600 m or deeper in some areas. With depths greater than 500 m, the CH_4 content increases rapidly until it reaches the primary methane zone with methane content of up to 15 m^3/Mg $coal^{daf}$. Going deeper, methane content tends to decrease. The northern pattern (A) is related to the Budryk mine, which is located in the north-western part of the basin (Fig. 1). Figure 4a illustrates the distribution of methane content in the Budryk coal seams (JSW—internal reports). The natural degassed zone is evident to the depth of 600 m, then methane content increases rapidly until the primary zone of methane content is reached. It is evident here, that thin and permeable Triassic and Miocene overburden is not sufficient to stop the migration of gases upwards (Table 3). The average and maximum CH_4 content in the Budryk seams tend to increase with depth, reaching maximum values of over 7 (average) and 15 (maximum) m^3/Mg $coal^{daf}$ between − 750 and − 990 m above sea level (between ca. 1000 and 1200 m below ground level). (Fig. 4). The depth range of the primary methane zone has not been exactly determined so far in the mine under study.

Figure 2 shows the fault distribution in the Budryk mine field (402 coal seam). These dislocations form a dense network of faults with latitudinal (Barbara fault zone) and

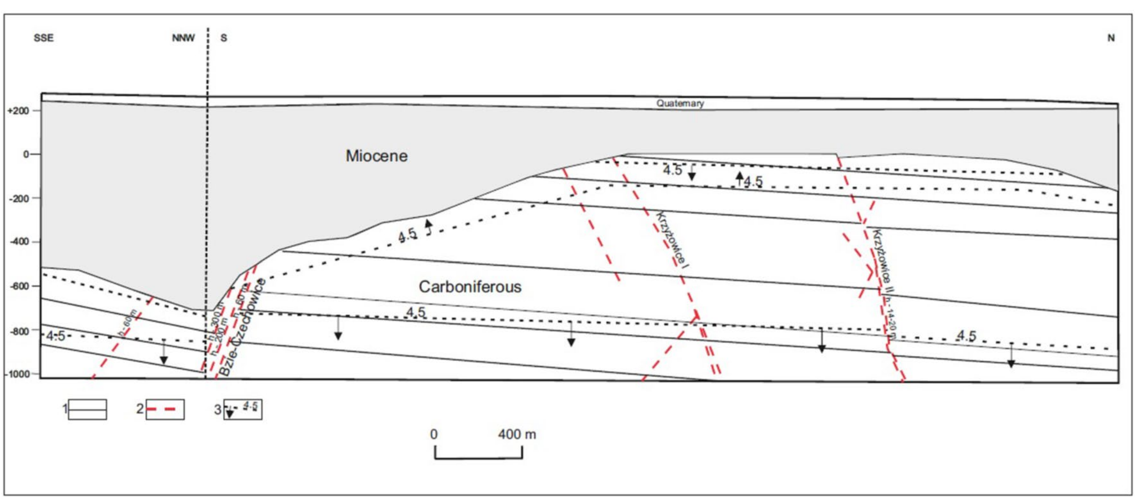


Fig. 3 The cross-section across the Pniówek Mine, 1—the more important coal seams, 2—fault with throw size h, 3—line of methane content 4.5 m^3/t $coal^{daf}$, increase in methane content in the direction of the arrow

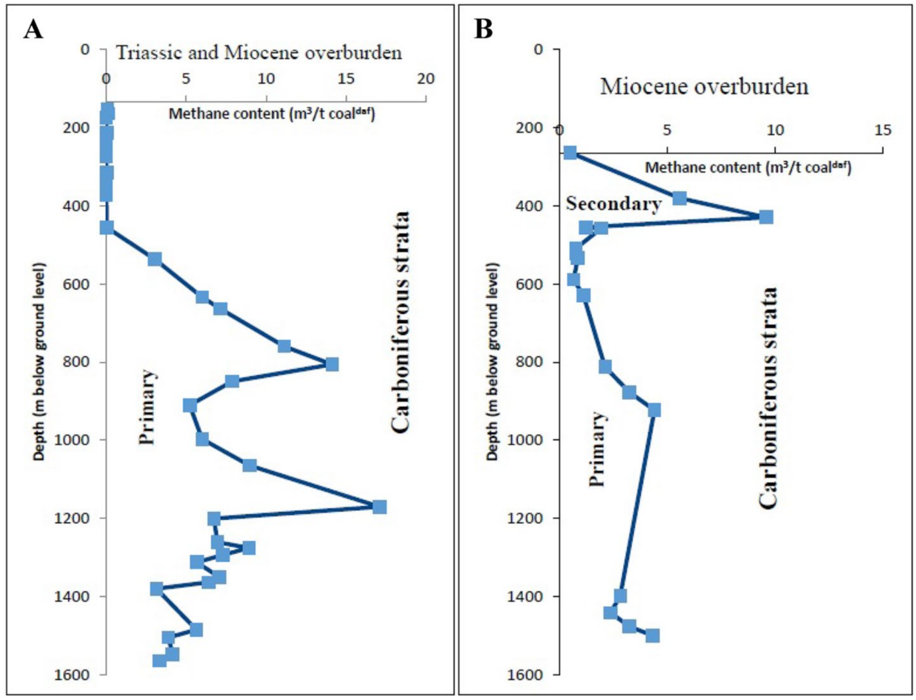


Fig. 4 Methane depth distribution in the Budryk (**a**) and Pniówek (b) mines. Primary – the primary methane zone in depth profile, secondary—the secondary methane zone in depth profile

longitudinal (e.g. Knurów and Chudecki faults) orientation (Table 1). The existing fault network probably aided the natural process of degassing the upper parts of the deposit in the geological past, and the faults themselves may today constitute the boundaries between the deposit parts with different level of gas saturation, and thus have different effects on the intensity of gas emissions to the mine workings of the Budryk mine. The role of faults in gas migration has also been studied elsewhere (e.g. Thielemann et al. 2001; Karacan and Olea 2014; Karacan et al. 2021).

Pniówek mine

Pattern B is associated with the southern part of the basin and includes two distinct zones of methane content (Fig. 4b). The first methane zone covers the secondary accumulation of CH_4 adsorbed in coal seams and free gas accumulated immediately below the thick and impermeable Miocene cover (Fig. 4b). The next methane zone, so called primary with increased concentrations of methane is separated by an interval of reduced CH_4 content in coal seams (400–800 m below ground level, Fig. 4b). The primary methane zone lies deeper (> 1000 m), with the CH_4 content of up to 10–16 m^3/Mg $coal^{daf}$ (Kotas 1994; Kędzior 2012). This zone contains thermogenic methane produced as a result of the coalification process in the late Carboniferous period (Kotarba 2001). Increased methane content in the uppermost part of Carboniferous coal-bearing series sealed with hermetic overburden is conditioned by the occurrence of microbial methane produced in the pre-Miocene period and then mixed with thermogenic methane (Kotarba and Pluta 2009; Kędzior 2019). The methane depth zones with faults in the area of the Pniówek mine are shown in Fig. 3. The main dislocation of Bzie-Czechowice, which is a regional dislocation in the basin scale, is located in the south of the studied area and displaces the primary gas-bearing zone in the throw direction (to the south, Fig. 3). Together with the remaining faults (e.g. Krzyżowice I and II), they seem to be migration pathways for gas between the primary and secondary methane zones. Probably thanks to them, thermogenic methane migrated towards the Carboniferous top and supplied the secondary gas-bearing zone (Kędzior 2009a, 2012).

The pressure of gas accumulated just below the Miocene cover is higher in comparison to the remaining parts of the Carboniferous series and oscillates around 6–7 MPa (Tarnowski 1971). After the Carboniferous period (especially in Mesozoic and Paleogene time), the top surface of coal-bearing formations were exposed and subjected to weathered and erosion processes. To the present, in the topmost part of the Pniówek coal deposit, a layer of coal-bearing detritus with a high 20–30% porosity has been preserved and now is sealed by the Miocene deposits. The currently observed zone of increased gas pressure is associated with porous coal-bearing weathered deposits in the Carboniferous top (Janas 1962; Tarnowski 1989), which is a reservoir of both secondary microbial gas and migrating thermogenic methane (Kotarba and Pluta 2009).

The differential vertical and horizontal methane distribution in coal basin caused by e.g. overburden occurrence, faulting and folding was identified in many coal basins (Ju et al. 2016; Diamond 1994; Noack 1998; Thielemann et al. 2001). The Pniówek mine corresponds to the southern pattern of the CH_4 vertical distribution (Fig. 4b). In contrast to the Budryk mine, the thick and impermeable Miocene Skawina Formation (Table 3) has prevented gases release from coal seams to the atmosphere in the geological past. A comparative description of the Carboniferous series overburden in both described mines is presented in Table 3.

Methane content vs. pressure and sorption capacity

The volume of adsorbed methane, in the same temperature and pressure conditions, depends on micropores and macropores content in coal. Kozłowski and Grębski (1982) showed that more microporous coals can accumulate more methane in the coal structure. Studies carried out on coals from Western Canada (Lamberson and Bustin 1993) revealed that vitrinite-rich coals have a greater sorption capacity than inertinite-rich colas in the same rank, however research from the 1970s (Harris and Yust 1976) displayed that coal micropores are predominantly located in vitrinite, while in the inertinite, meso- and macropores. Moreover, the temperature and moisture have a negative influence on the sorption capacity of coal (Kozłowski and Grębski 1982; Kędzior 2009b, 2019; Wierzbicki 2013). The gas (methane) pressure in the coal seam is determined by the methane content in coal (Tarnowski 1989, 1971; Lunarzewski 1998) and is defined by the desorption intensity. This method is commonly used in the Polish and worldwide mining industry (Kozłowski and Grębski 1982; Lama and Bodziony 1998; Wierzbicki and Skoczylas 2014; Krause 2019) to classify the methane danger, before the more accurate tests will be carried out by the certified mining laboratories. The collected data of the gas pressure, in the southern part of the Upper Silesian Coal Basin by Tarnowski (1971) revealed that methane content in the coal seam is fairly correlated with the methane pressure/desorption intensity (Fig. 5). The recent results of tests made by the CLP-B Sp. z o.o. in Jastrzębie-Zdrój (Poland) for the Budryk and Pniówek mines for the years 2018–2020 showed similar outcomes describing the methane content and gas desorption/pressure interdependence (Fig. 6a, b).

Coal mining

The most important economic factor in every mine is the annual coal production. Economic possibilities, natural hazards, technical difficulties and market size affect the annual coal output of each mine (Dreger 2019, 2020; Dreger and Kędzior 2019). Changes in coal production over time in both analysed mines are illustrated in Fig. 7.

The Budryk mine started production in 1994, while the production data from Pniówek starts from 1986. In 1994, the Budryk mine was getting started with just 580 thousand Mg of extracted coal (Fig. 7). Over the following years, coal production in Budryk was gradually increasing, reaching the highest production level in 2007 with 3.85 million Mg of extracted coal. In subsequent years, until the end of the study period, coal output dropped and retained a constant level of under 3 million Mg per year.

On the other hand, the highest hard coal output in Pniówek was reported at the beginning of the research period, in the late 1980s, with the coal production exceeding 3.8 million Mg. In the next years, to the end of the studies, the coal production fluctuated which can be seen on Fig. 7.

Hard coal extraction in Polish underground mining is deeper about 8 m per year on average (GIG 1995–2019). As a result, coal production takes place in coal seams of variable gas and physico-chemical conditions. In most mines, in the USCB, methane content increases with increasing depth (Kędzior and Dreger 2019; Krause 2019). As the depth of extraction increases, gas permeability in coal seams decreases and pre-mining methane drainage is not sufficient; therefore, the methane hazard increases. The average depth

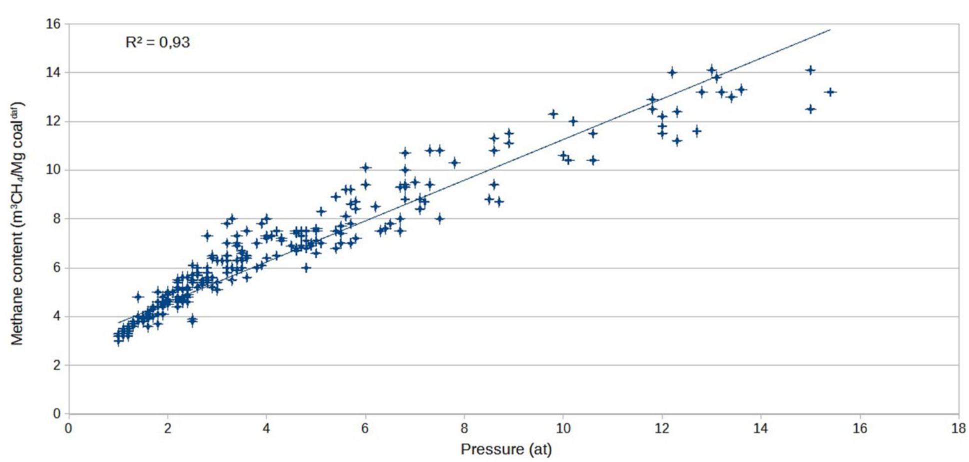
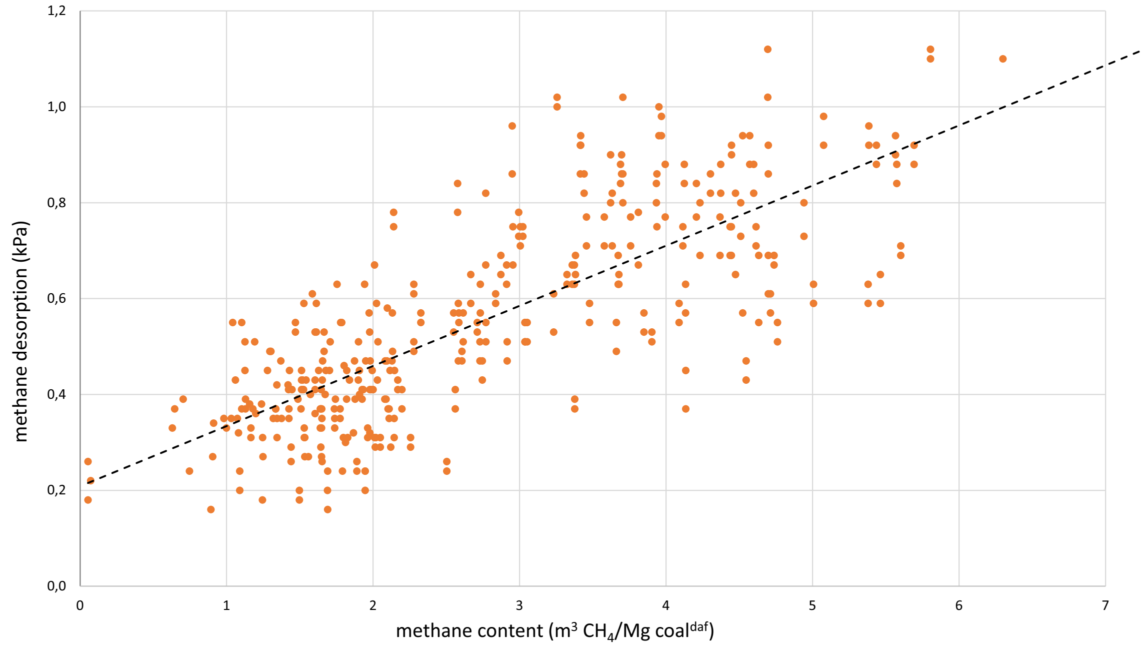
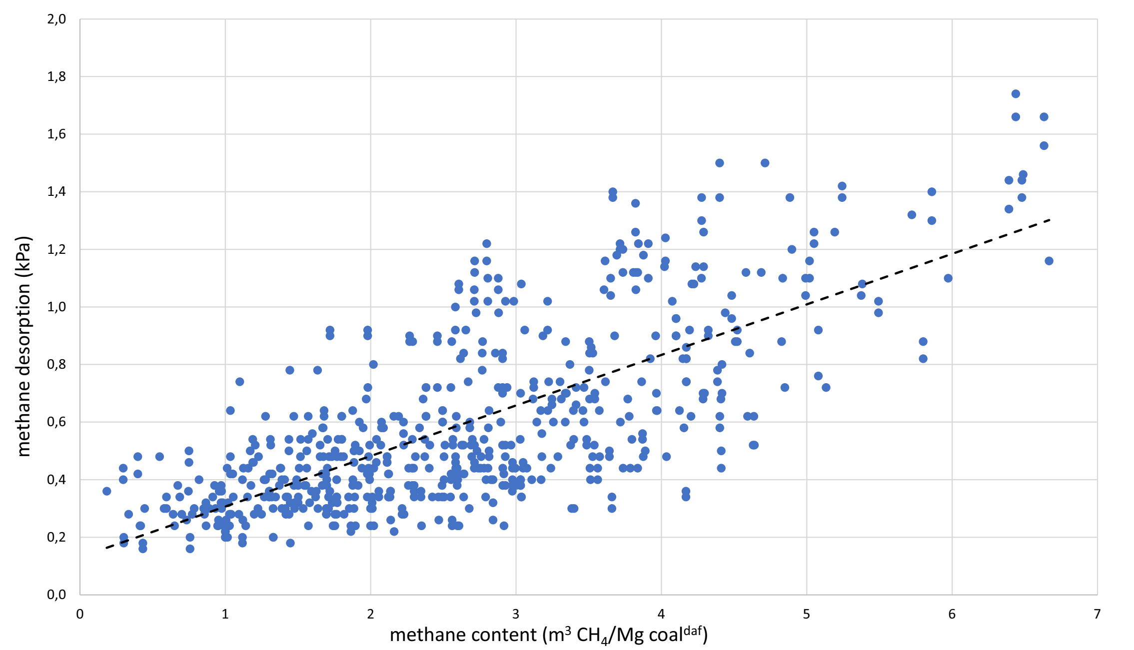


Fig. 5 The methane content and coal seam pressure studied in the USCB coal mines (Tarnowski 1971)



(a) The methane content and coal seam pressure studied on Budryk's coals by the CLP-B Mining Laboratory



(b) The methane content and coal seam pressure studied on Pniówek's coals by the CLP-B Mining Laboratory

Fig. 6 **a** The methane content and coal seam pressure studied on Budryk's coals by the CLP-B Sp. z o.o. **b** The methane content and coal seam pressure studied on Pniówek's coals by the CLP-B Sp. z o.o.

of coal extraction in 2010 was around 700 m, and from year to year it was permanently increasing by 8–10 m. Now, the average depth of coal production is 788 m and coal sorption capacity is much lower than in shallower seams and the gas pressure in coal seams increases with depth (GIG 1995–2019; Kotas 1995; Krause 2019; Szlązak et al. 2020). Studies conducted by Krause (2019), e.g. revealed that most of the methane emitted to the coal workings comes from

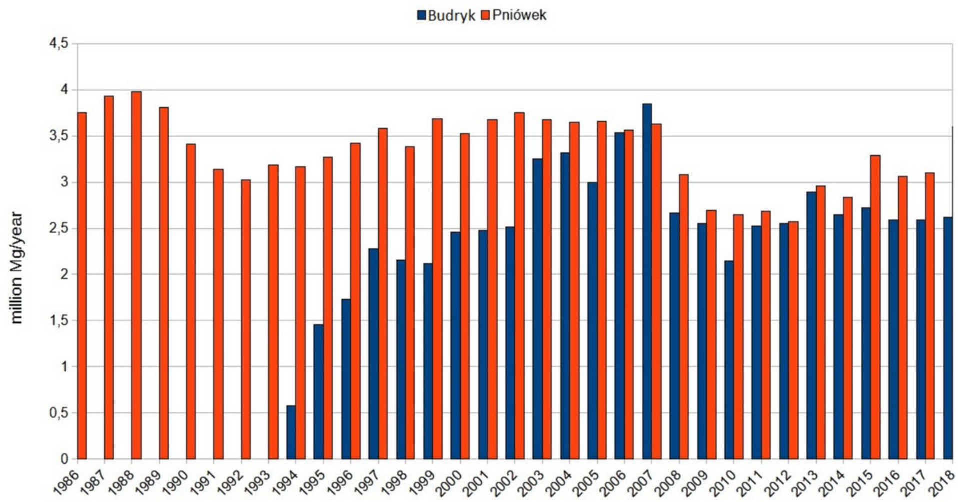


Fig. 7 The Budryk and Pniówek hard coal output (JSW—internal reports, GIG, 1995–2019)

depleted, overlying and underlying coal seams (60%), the remainder of CH_4 is emitted from extracting longwall (40%). Another important factor is the intensity of coal production. Hard coal in the USCB is almost exclusively produced by means of longwall systems with the use of heading machines and longwall mechanical coal miners (Krawczyk 2020). Longwall length and height, daily extraction progress are the main variables needed to determine the amount of the coal output. The longwall length increased by ~ 41% in recent years, coal production intensity rose and total methane emission also increased (Turek 2007; Krause 2019). As longwall length increases, the area of exploitation relaxation rises and the volume of released and migrated methane is also higher.

In the Budryk mine, with the greatest depth of mining in the USCB, currently reaching 1290 m, the number of operating walls has been changing during the studied period of coal production (1994–2018). Hard coal production at production levels becoming deeper every year does not change the technical parameters of extracting walls. No significant concentration of coal extraction was found, as the parameters of longwalls change regardless of the year, depth and amount of coal extracted changes.

During the last 4 years of the study, the average depth of coal production in the Pniówek mine rose from − 613 (2015) to − 665 m above sea level in 2018 (about 880 in 2015 to 930 m below ground level in 2018) which was 13 m deeper every year. Between 2015 and 2018, a greater amount of coal production was observed (JSW—internal reports).

Methane emissions

Budryk mine

The CMM from all the coal excavations of the Budryk mine was measured in the period from 1994 to 2018. From the beginning of the study to 2005, the total methane emission rose from 2.21 to 55.80 million m^3/year (Fig. 8). In subsequent years (2006–2012) methane emission was around 40 million m^3 of gas per year. From 2013 a large increase in methane emission was observed; in the last three years of the study (2016–2018), over 140 million m^3 of CH_4 was emitted yearly, which was three times more than the average emission in 1994–2012.

At the beginning, coal was mined at shallower, naturally degassed seams but when coal mining entered into a deeper zone with higher methane content, the total CH_4 emission increased rapidly. The methane content and gas pressure increase with depth within the Main Trough area, including the Budryk mine, what is the main reason of the large increase in methane emission at greater depths in the mine. The related data, such as degassing, ventilation air methane (VAM), and specific methane emission, follow the trend of the total methane emission (Fig. 8). The Budryk mine started degassing of the coal seams in the fourth year after coal extraction had been started (in 1997) (Fig. 8). Before that time, all of the methane was released directly to air. It is worth mentioning that from 1997 to 2013 between 30 and 50% of all of the emitted methane was captured by the underground methane drainage system. When the total methane emission suddenly rose in the last 5 years of the research period, the share of degassing and utilising methane in internal mining processes also increased, to reach 70–88% in the period 2014–2018. The specific methane emission shows the real methane hazard that miners and mining authorities have to deal with. From the beginning of the research period to 1998 the specific methane emission was below 10 m^3/Mg of extracted coal (Fig. 9). From 1999 until 2013 the amount of emitted gas was oscillating between 10 and 20 m^3 of CH_4 (Fig. 10). In the last five years of the study, the specific methane emission increased to 26 m^3/Mg and was doubled (54–59 m^3/Mg) in 2016–2018 (Fig. 9). The Budryk mine, as the youngest working coal mine in Poland, started

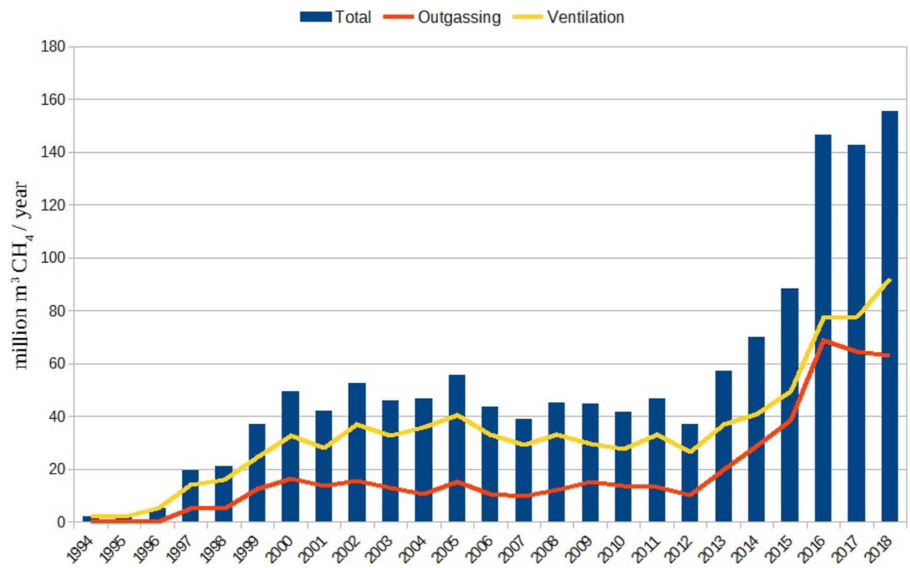


Fig. 8 The Budryk mine methane emissions (JSW—internal reports)

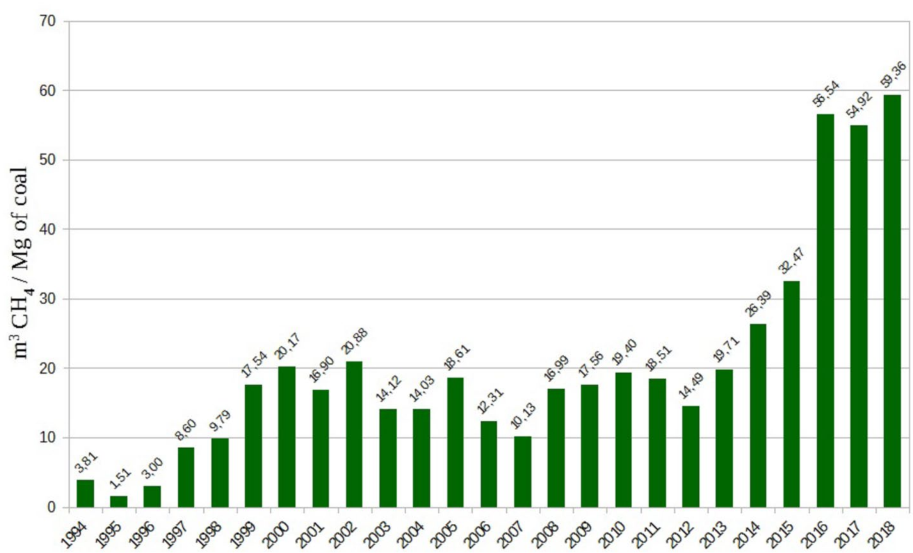


Fig. 9 The Budryk mine-specific methane emission (JSW—internal reports)

coal extraction in 1994. In the geological past, shallow lying coal seams (up to about 500–600 m deep) were naturally degassed, owing to erosion and hydrodynamic changes in the rock mass in the northern part of the USCB before the Miocene period. The degassing process was facilitated by faults constituting migration pathways for methane. As a result, methane emission values correspond to the pattern A of the vertical methane distribution in the USCB. Shallower seams were emitting less than 40 million m^3 of CH_4 yearly during mining activities. As the depth of extraction increased, entering the primary methane maximum at the depth of 600 m (Fig. 4), the CH_4 emission to mine excavations increased rapidly, exceeding 140 million m^3 of gas in the last three years of the study (2016–2018). The increase in methane content in coal seams and surrounding rocks results in an increase in gas pressure in the rock mass (Figs. 5, 6a), which also affects the intensity of methane emission into mine workings.

Pniówek mine

The Pniówek coal mine has been producing coal much longer than Budryk; hence, all the data come from the period 1986–2018. When we take a look at the total methane emission and the related emission data, we will see that those trends are completely different than in the Budryk mine. The largest total CH_4 emission values were observed in the late 1980s and at the early 1990s, when the coal was mining just below the sealed Miocene strata, where methane was accumulated in the coal seams as well as in porous

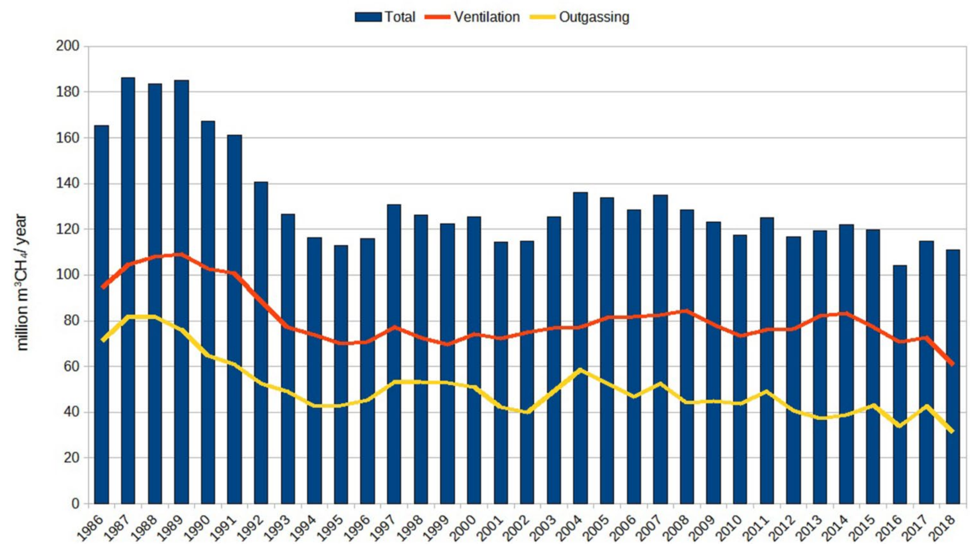


Fig. 10 The Pniówek mine methane emissions (JSW—internal reports)

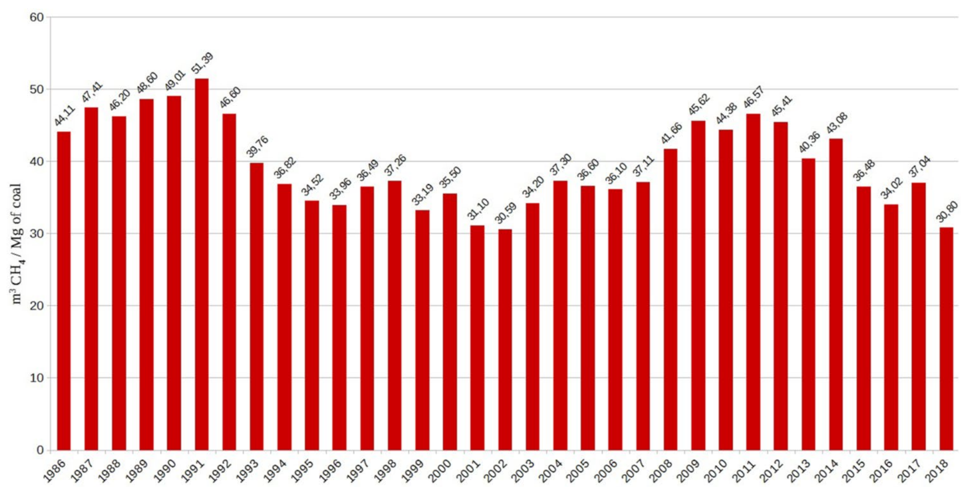


Fig. 11 The Pniówek mine-specific methane emission (JSW—internal reports)

rock strata in the geological past, forming the local methane maximum associated with the pattern B of the USCB vertical CH_4 distribution (Sect. 4.1, Figs. 3, 4). The largest coal mine methane emission was reported in the period 1987–1989, when over 180 million m^3 of gas was released to mine excavations over a one year period (Fig. 10). In subsequent years, the emission was decreasing from over 167 million m^3 in 1990/91 to the average of 123 million m^3 yearly during the next 26 years' period (1992–2017). The VAM adopts a similar trend as the total CH_4 emission, reaching maximum values from the beginning of the research to 1991, with the highest value in 1989, when over 109 million m^3 of this dangerous gas was discharged out of the mine (Fig. 10). Over subsequent years, the VAM trend is stable with small rises and decreases, reaching the lowest value similar to that of the CMM in 2018, when only 60 million m^3 of gas was removed by the ventilation systems out of the mine (Fig. 10).

Between 1991 and 2008, we can observe a decrease in specific methane emission with over 30 $m^3$of methane emitted per one Mg of coal (Fig. 11). In 2008–2014, the CH_4 emission over 40 m^3/Mg was noticed with slight, but constant decrease in the following years until the end of the study period when the lowest emission was recorded: 25.51 m^3 of CH_4/Mg in 2018. In the period 2015–2018, coal production increased to over 3 million Mg/year and the total methane emission decreased to under 120 million m^3/year (Fig. 10).

Due to complex and diversified faulting (Figs. 2, 3), geological structure and deeper coal extraction every year, the methane emission fluctuates in both mines with consistent trends. In the Budryk mine, the trend is increasing, but in the Pniówek mine, it is slightly, but constantly decreasing. Despite the different methane liberation trends, the total CH_4 emission in both mines remains at the highest level in the

Upper Silesian Coal Basin throughout the entire research period.

In addition to methane emissions in the Pniówek mine, much more dynamic events took place in the form of gas and rock outbursts. In 2002, during the blasting operations at the level of 1000 m, there was an outburst of approx. 250 m^3 of grinded down coal and ejection of ~ 55,000 m^3 of methane. The concentration of released methane in the mine air increased to ~ 86%.The gas and rock outburst in the neighbouring Zofiówka mine in 2005, which took 3 fatalities, resulted from the accumulation of methane in the mylonitic coal accompanying the two fault zones (Młynarczuk and Wierzbicki 2009; Jakubów et al. 2006; Kędzior 2012). The vertical distribution of methane content observed in the Pniówek mine is different from that in the Budryk mine. The difference concerns the occurrence of the zone secondarily saturated with methane under the Carboniferous top, which is evident by the high gas content in coal seams lying in this zone (Sect. 4.1.). The zone of increased pressure of free gas (7–8 MPa) associated with porous detritus lying at the uppermost part of the Carboniferous sediments is also important (see Sect. 4.1). Thus, coal extraction at the beginning of the study, when shallower seams were operated, was conducted under a higher methane hazard than when it was carried out in deeper seams in subsequent years. The secondary methane accumulation with methane content exceeding 10 m^3/Mg $coal^{daf}$ placed under the Miocene cover and also the occurrence of many faults (Fig. 3, see Sect. 4.1), considered as migration pathways for methane, were the cause of the high methane emission (over 160 million m^3 CH_4) to coal workings in a year period. In subsequent years, the total methane emission dropped to over 90 million m^3 in 2018, which may be associated with a decrease in the methane content of the seams as the depth of extraction increased and as it entered the zone of reduced gas content and pressure. The deeper occurring primary gas-bearing zone has a lower methane content (< 10 m^3/Mg $coal^{daf}$) than in the case of the secondary methane zone adjacent to the Miocene overburden (about 10 m^3/Mg $coal^{daf}$) (Fig. 4).

To sum up, methane emissions in the studied mines are the result of natural factors (geological and gas content of the rock mass), influencing in the first place, and anthropogenic (mining) aspects acting additionally. Details are shown in the Table 4.

Environmental aspect

Methane was recognized as the second-most important and powerful anthropogenic greenhouse gas (GHG) with a global warming potential (GWP) ranging from 20 to 36 times greater than carbon dioxide over a 100-year time period and 86 times greater over a 20-year period (Archer 2011; IPCC et al. 2013; Etminam et al. 2016; US EPA 2019a). Coal mining production is one of the largest sources of the methane emission, estimated for 11% of CH_4 emitted worldwide (US EPA 2019a, b; Global Methane Initiative 2020). Globally, the main methane emittants are: agriculture, wastes, biomass, coal mining, fuel combustion and natural emissions (Yusuf et al. 2012; Global Methane Initiative 2020). In Poland, the methane emitted to the atmosphere from underground coal mining accounts on 33.8% total methane emission in the country (Institute of Environmental Protection-National Research Institute 2020; Dreger 2021). When coal is mined, large amounts of CH_4 are released from coal and surrounding strata to the mining atmosphere due to drilling, grounding, transportation, explosives, etc. (e.g. Karacan et al. 2011; Kędzior and Dreger 2019). Methane

Table 4 Summarized division of the factors influencing the methane emissions in the Budryk and Pniówek Mines

Factors influencing the methane emissions		
Group of factors	Budryk mine	Pniówek mine
Natural (acting in the first place)	Geological—thin and permeable overburden of coal-bearing strata, deep reaching natural degassed zone Faults distribution, dislocations probably aided the degassing process of the upper parts of the deposit Gas content and pressure increasing with depth	Geological—thick and impermeable (sealing) Miocene overburden Secondary zone of increased methane content and elevated gas pressure placed in the uppermost part of the Carboniferous strata The occurrence of the primary and secondary zones of gas content and pressure in depth profile of coal-bearing sediments Fault tectonics, faults considered as migration pathways for methane and often responsible for gas and rocks outbursts
Mining (additionally acting)	Concentration of coal output Wall length, height and advance increase Methane emissions from now operating longwalls, underlying and overlying coal seams, as well as abandoned workings and goafs Depth of coal extraction	

emitted to the atmosphere is a mixture of unused captured gas (from underground drainage) and methane coming from the ventilation air emission (Tutak and Brodny 2019; Dreger 2021). Methane emission from mining ventilation shafts contributes the most to global methane emission from mining industry, nevertheless CH_4 is a potent source of energy and can be collected by underground drainage and can be used economically in the future (Global Methane Initiative 2020; Swolkień 2020; Dreger 2021). Unfortunately, in the Upper Silesia Coal Basin only 25% of all emitted methane is captured by underground drainage system. The vast majority of released gas to the coal workings is disposed by VAM (75%) (Tutak and Brodny 2019; Dreger 2021; Szlązak and Swolkień 2021). Unluckily, it is impossible to capture all of the emitted gas and gas mixture in the areas affected by mining works. The greenhouse effect magnification from coal mines does not stop, even when the mine is closed. The methane liberation from non-extracted coal seams, overlying and underlying seams can be active up to 15 years after colliery closuring. This problem was the purpose of numerous studies (e.g. Pokryszka and Tauziede 2000; Franklin et al. 2004; Krause and Pokryszka 2013; Kholod et al. 2020).

Besides the great heat absorption, methane is harmful to the human health and crops. There were recognized many indirect effects of CH_4 emission like heart and lungs diseases and yield losses (West and Fiore 2005; UNEP Synthesis Report 2011).

In 2018, over 1.9 million Mg of methane was emitted in the territory of Poland, including 0.53 million Mg from the USCB coal mines. It is worth to mention that 20% of all emitted GHG in Poland is covered by CH_4 but Polish gassy mines are responsible for only 3% GHG in the country (Dreger 2021). Coal production industry in Poland and worldwide will be struggling with more complex geological and mining conditions and also, with greater depths of mining when more methane is going to be emitted (Kędzior and Dreger 2019; Tutak and Brodny 2019; Karacan et al. 2021). The development of VAM gas production is the key solution to limit the CH_4 emission to the atmosphere. However, in Poland, to ensure safety, the concentration of methane in the VAM has to be reduced to $\leq 0.75\%$ in the ventilation shafts. Thus, the energy production from low caloric fuel is ineffective (e.g. Honysz 2015; Szlązak and Swolkień 2021). Globally, several technologies were developed to use air mixture with low CH_4 concentration in the turbine engines. The list of technologies can be found at: CMM energy (2021), EPA (2019a, b), Szlązak and Swolkień (2021).

Conclusion

The Budryk and Pniówek mines belong to the most gassy mines in the Upper Silesian Coal Basin. However, both are located in different parts of the basin, which are characterised by both different geological structure and spatial distribution of gas content. At the Budryk mine, the youngest in the basin, coal mining was initially carried out (1990s) in a shallow naturally degassed zone, then it entered into a deeper zone with high methane content of 12 and more m^3/Mg coal^{daf}. This resulted in a sharp increase in methane emissions from around 2 to over 140 million m^3 of methane per year (late 2010s).

At the Pniówek mine, coal was initially mined in high-methane seams occurring in the secondary methane-bearing zone with high methane content in coal seams (> 10 m^3/Mg coal^{daf}) and elevated free gas pressure (7–8 MPa) in weathered rocks, located just below the sealing Miocene overburden. This resulted in record-high methane emissions in the initial extraction period (1980s), reaching 180 million m^3 annually. In subsequent years, methane emissions decreased to around 100 million m^3 in 2018 with numerous fluctuations throughout the entire research period. This can be explained by the lower methane content and gas pressure in coal seams at a greater depths associated with the occurrence of a reduced methane content zone and the primary gas-bearing zone occurring deeper, but with a lower gas content than the shallow, secondary one. Thus, it may seem that the vertical zonation of the gas content in seams is the main factor that controls methane emissions in the analysed mines, because the temporal variability of methane emissions coincides with the depth of coal extraction corresponding to individual gas zones.

Faults, breaks and rock discontinuities are an important factor of methane migration, because in their vicinity a decrease or increase in gas content and gas pressure has been observed. Often, methane had migrated through faults in the geological past, and thus fault zones can also be now a source of methane emissions into mine workings. In special circumstances, they can also cause more dynamic phenomena, such as gas and rock outbursts, which took place in the Pniówek and Zofiówka mines.

Also important are the mining factors affecting methane emissions, such as the intensity of coal mining, the size of the mining longwalls, their number and the presence of goafs, which are an important source of methane emissions. Along with significant methane emissions in both mines, methane is captured by methane removal stations, which has a positive impact on safety of miners at work, economic balance of the mines and environmental protection (reduction of greenhouse methane emissions to the atmosphere).

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent The authors have all the consents for using data and information from Jastrzębska Spółka Węglowa SA (JSW SA) and from the CLP-B Sp z o.o. in Jastrzębie Zdrój. All experiments which were done during research comply with the current law of the Republic of Poland.

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