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Factors that influence the temporal variability of atmospheric methane emission from Upper Silesia coal mines: A case study from CoMet mission.

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Abstract:

Errors in assumed pollutant emission characteristics can significantly impact the magnitude of the estimated emissions constrained by instantaneous observations obtained with airborne or remote sensing instruments, especially on the local scale. Realistic emissions from individual point sources are a valuable input for numerical models, as by minimizing the errors stemming from inaccurate emissions, they could allow a better characterization of errors caused by transport mechanisms.

Here we provide a detailed description of factors influencing the coal-mine methane emission variability, based on high-frequency (up to hourly) temporal data obtained from seven coal mines from the Upper Silesian Coal Basin during CoMet 1.0 (Carbon dioxide and Methane) mission which took place from May 14 to June 13, 2018. The knowledge of these factors for the particular ventilation shaft is essential for linking the observations achieved during the CoMet 1.0 with models, as most of the publicly available data in the bottom-up worldwide inventories provide annual emissions only.

The methane concentrations in examined shafts ranged from 0.10 % to 0.55 % during the study period and were subject to a significant variation on a day-to-day basis due to the changing scope of mining works performed underground. The yearly methane average emission rate calculated based on temporal data of the analyzed subset of mines was of the order of 142.68 kt yr^{-1}, an estimate lower by 27 % than the oficially published WUG (State Mining Authority) data and 36 % than reported to E-PRTR (European Pollutant Release and Transfer Register). Additionally, we found that emissions from individual coal mine facilities were over- or underestimated by between 4 % to 60 %, compared to E-PRTR, when short-term records were analysed. We show that the observed discrepancies between annual emissions based on temporal data and public inventories result from, firstly, the incorrect assumption that the methane concentrations in the time-invariant, secondly, from the methodology of measurements, and lastly, from frequency and timing of measurements.

From the emission monitoring perspective, we recommend usage of a standardized emission measurement system for all coal mines, similar to the the SMP-NT/A methane fire teletransmission monitoring system (which most coal mines are equipped with). Such a system could, allow for gas flow quantification, necessary for accurate and precise estimations of methane emissions at high temporal resolution. Using this system will also reduce the emission

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uncertainty due to factors like frequency and timing of measurements. In addition, separating the emissions from individual ventilation shafts and methane drainage stations would be beneficial in closing the gap between bottom-up and top-down approaches for coal mine emissions, as the intermittent releases of unutilized methane from the drainage stations is currently not considered when constructing regional methane budgets.

1. Introduction

Methane is a greenhouse gas emitted from a wide variety of highly dispersed sources that overlap geographically. Methane has a lower atmospheric concentration relative to CO_2, but a global warming potential (GWP) 28 times higher (on a 100-year horizon) than that of CO_2 (Myhre et al., 2013; IPCC, 2014). More recent studies even suggest the GWP to be even 32 times higher (Etminan et al., 2016). When additional carbon footprint is considered as well, it amounts to 34 on a 100-year horizon and 86 on a 20-year horizon (Myhre et al., 2013). Although its global emission accounts for about 4 % of the anthropogenic CO_2 emission in mass flow units, it is nevertheless responsible for ~ 20 % of the additional radiative forcing accumulated in the lower atmosphere since 1750 (Saunois et al., 2020). Considering that its emission sources have not been fully ascertained, our ability to accurately predict future climate change is still challenged. Therefore, it remains of utmost importance to reduce the uncertainties in the estimated amount of released methane across a wide array of natural and anthropogenic emission sources, including coal mines.

To that end, attempts at improving the emission estimates are generally made following two methodologies: first, where emission are derived and subsequently aggregated from available activity data (the so-called bottom-up approach) or process-based models, and second, in which the results of direct atmospheric observations (from the ground, aircraft, and satellites) are used together in tandem with atmospheric transport models of various complexity to derive those emission estimates - the so-called top-down approach (e.g. Saunois et al., 2020, 2016).

Bottom-up approaches involve publicly available databases such as UNFCCC Greenhouse Gas Inventory Data (*United Nations Framework Convention on Climate Change*), EDGAR (*Emissions Database for Global Atmospheric Research*), or the UNFCCC Scarpelli database (UNFCCC database, Scarpelli et al., 2020; Höglund-Isaksson 2012; Saunois et al., 2020). These inventories are based on different assumptions and use different data sets in calculations but follow the same IPCC Guidelines. For instance, UNFCCC provides CH_4 emissions from underground coal mines which are reported according to the guidelines for Annex I and non-Annex I countries. For Poland, these originate from the State Mining Authority inventory (Wyższy Urząd Górniczy, WUG, 2019). On the other hand, the EDGAR database compiles consistent anthropogenic global emissions and trends based on international statistics and technology-based emission factors, for the use in atmospheric models and policy evaluation. Additionally, EDGAR provides global emission estimates, disaggregated at the source-sector level (Crippa et al., 2021; Janssens-Maenhout et al., 2019). As a result, the former databases require a vast amount of country-specific information, and if not available, coefficients suggested by IPCC are used instead (Höglund-Isaksson 2012). Valuable inventories were also developed on regional scales. In European Union, E-PRTR database (European Pollutant and Transfer Register) was implemented in 2006 in response to the Aarhuus Convention. The E-PRTR database contains emission data reported annually by individual facilities from 27 European Member States whose emissions exceed the threshold of 1 kt CH_4 per year.

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Top-down approaches involve methods based on state-of-the-art measurement technologies using satellites, ground-based measuring devices, and aircraft (Fix et al., 2018a; Gurney et al., 2002; Houweling et al., 2017; Bergamaschi et al., 2018; Saunios et al., 2020). Currently, the existing possibilities of monitoring the concentration of greenhouse gases are in-situ (the sensor or probe installed in the place of measurement) and active and passive remote sensing (Fiehn et al., 2020; Kostinek et al., 2020; Amediek et al., 2017, Fix et al., 2020; Bovensmann, 2019). In addition, it is possible to conduct ground-based measurements using FTIR (Fourier Transform Infrared Spectroscopy) devices (Luther et al., 2019).

In order to implement an integrated system for methane or carbon dioxide emission monitoring both approaches to support each other are deemed necessary. However, one of the most critical issues is obtaining temporal emission from individual point sources (Swolkień, 2020). Previously mentioned bottom-up inventories cover either annual (UNFCCC, E-PRTR) or monthly (EDGAR) aggregates of released CH_4 (UNFCCC, E-PRTR). Temporally resolved data at higher frequencies are not available in any of the existing databases, despite being necessary to provide estimates more accurate than standard inventory data (Swolkień, 2020). Higher temporal resolutions could also improve predictions of high-resolution atmospheric transport modelling. Therefore all efforts to monitor the temporal evolution of individual sectors, not just yearly averages, need stronger support and will constitute a significant advancement in the National Reporting to the UNFCCC. Moreover, temporal variation of concentrations on various time scales can serve as additional constraints to separate methane emissions from different sectors.

As methane emissions into the atmosphere are a matter of great concern, available methods are employed to conduct large-scale research geared towards introducing an integrated system for monitoring greenhouse gas emissions (Fix et al,. 2018a). An example of a campaign aimed at improving the methodology for measuring the efficiency of gas streams (CO_2, CH_4) at a local and regional scale (Fix A. et al., 2015; Fix et al., 2018b; Fix et al., 2020) was CoMet 1.0 (Carbon dioxide and Methane) that took place in May and June 2018 (Fix et al. 2020; Luther et al. 2019). The campaign combined active (lidar) and passive remote sensors (spectrometer) with in-situ instruments installed onboard the German research aircraft HALO, two smaller aircraft (Cessna 208 Grand Caravan, Cessna 207), as well as ground-based measuring devices and by drones (Luther et al., 2019; Fix et al., 2018a; Galkowski et al., 2019; Bovensmann et al., 2019, Andersen et al., 2021; Andersen et al., 2022).

The goals of the mission was to comprehensively measure the distribution of greenhouse gases and, in conjunction with modeling activities, investigate and improve methodologies to estimate local and regional fluxes of greenhouse gases from anthropogenic sources such as coal mining. For these investigations, the USCB was deemed an interesting test case.

The primary purpose of the paper in hand is to explain the nature of methane emission from Polish underground coal mines localized in the USCB and its temporal variability in order to link the mining and atmospheric science perspectives. We describe the factors that significantly influence the methane concentration variability while emphasizing their importance concerning the annual data available in the bottom-up inventories available worldwide. The knowledge of factors affecting methane concentrations variability in the particular ventilation shaft, treated as a point source of methane emission, is essential for verifying the data achieved during the CoMet 1.0 campaign, improve models and prepare for future exercises.

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The first part of the article explains why USCB was adopted as a research area during the CoMet 1.0 mission. The second treats the methodology of methane concentration measurements in selected coal mines. The third part is devoted to describing and explaining different factors affecting the variability of concentrations and fluxes from ventilation shafts. It also compares the temporal data with WUG and E-PRTR inventories.

2 Description of the methane emissions and their capturing from the USCB area

Methane emitted from active coal mines is generally referred to as CMM (Coal Mine Methane), in contrast to AMM (Abandoned Mine Methane) which refers to emissions from closed mines (Swolkień 2015; Boger et al., 2014; Karacan et al., 2011).

The methane released from active coal mines (CMM), also referred to as total methane bearing capacity or total methane emission, consists of two components:

- drained methane is the methane captured by the drainage system,
- ventilation air methane (VAM) is the methane released to the excavation and removed via ventilation shafts,

Poland is the tenth-largest coal producer globally, with domestic extraction of the order of 63.4 million tonnes (IEA 2019) in 2018 . At the same time, Polish emissions of CH_4 from underground mining are ranked seventh in the world, with 2 % of the total methane emitted from this source category in 2018 (UNFCCC database). According to the 2020 National Inventory Report (NIR), the total CH_4 emission in Poland amounted to 1950 kt, which represents a decrease of 35.6 % from the base year (1988), with over 30 % of country's total CH_4 emissions coming from the mining sector in 2018 (NIR 2020). Poland is the largest contributor of coal-mining methane in Europe, responsible for a total of 604 kt released to the atmosphere according to UNFCCC, corresponding to 41 % of the total emissions from this sector (Fig. 1). Other large contributions came from Ukraine (35 %), Romania (14 %), Germany (4 %) and Czechia for 3 % of total CH_4 emission, with the rest being small contributions from other countries. It should be noted that these statistics do not include the Russian Federation, which emitted 1462 kt in 2018, as separate data from European part of the country is not available from UNFCCC (https://di.unfccc.int/detailed_data_by_party)

According to Polish State Mining Authority (WUG) in Poland, the CMM emissions from the rock mass affected by mining reached 656 kt CH_4, which on average equaled to 1.25 kt per minute (Table 1) (WUG, 2019).

Most of the Polish methane emissions from mining originate from the Upper Silesia Coal Basin (USCB), country's largest industrial district, heavily dependent on the mining industry even today. According to the 2019 balance of mineral resources and underground water in Poland, methane in hard coal seams has been appropriately documented only in the Upper Silesian Coal Basin (PIG-PIB, 2020). To date, no detailed examination of these has been carried in the collieries of the other two major coal excavation regions (Lower Silesian Coal Basin and of the Lublin Coal Basin). Reconaissance study by Szlazak et al (2014) showed, that the levels of methane concentration in the latter areas are considerably lower, which makes it difficult to assess their economic significance.

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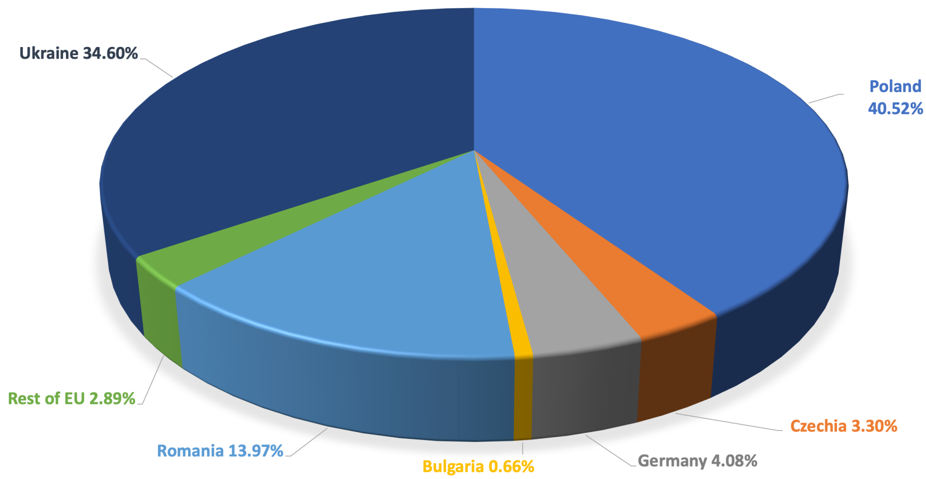

Figure 1. Share of atmospheric methane emissions from underground coal mines in Europe in 2018 (UNFCCC, https://di.unfccc.int/detailed_data_by_party)

As of 2018, 29 active coal mines were operational in USCB, covering an area of 5600 km^2 (WUG, 2019), 6 of which were in the state of liquidation, meaning a slow reduction of activity towards shutdown, usually lasting several years. Figure 2 presents the map of the mining areas of the USCB with the indication of the mines with verified methane release (WUG, 2019) and also ventilation shafts that were targeted during the CoMet 1.0 mission. It is important to note that due to restructuring efforts undertaken in the past 30 years, coal mines can nowadays operate either as an individual facility or in a combined entity consisting of two or three of these individual facilities (also referred to as fronts). As the emission reporting is only required on a facility level, it is difficult to track emissions from individual fronts over the years, as their respective totals might be assigned to a different combined entity on a year-by-year basis. For the sake of clarity, each coal mine reported in this paper will be referred to as an individual facility.

The geological structure of the deposit located in the USCB region favors gas migration. Methane that exists in the coal bed was produced in the process of carbonization of organic substance. The potential to release methane per 1 tonne of extracted coal is referred to as the specific methane emission and calculated by dividing the total methane bearing capacity in a given year by the annual production. For Polish coal deposits it reached 14.4 m^3 t^{-1} (see Table 1) in 2018 and in 2013-2018 this rate increased from 11.1 to 14.4 m^3 t^{-1}. The value of this factor, together with coal output, is used as activity data for calculating atmospheric methane emissions in inventories such as UNFCCC. Apart from Poland, mines characterized by high specific methane content are abundant in e.g. Russia, Ukraine, China, the United States of America, and the Czech Republic (IPCC, 2014).

USCB inventory estimates available in E-PRTR (European Pollutant Release and Transfer Register) for 2018 show that depending on the individual mining facilities or fronts, CH_4 emissions amounted to 2.00 kt and 78.40 kt (E-PRTR, 2018). On the other hand, WUG stated that the CH_4 emissions for individual mining facilities and combined entities ranged between 0.14 kt and 66.14 kt (WUG, 2019) in that year. It is worth noting that the two emission inventories

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differ slightly in the methodology of compiling the results. In the WUG inventory, the total atmospheric methane emission is calculated based on individual facilities' and combined entities' ventilation air methane and the amount of non-utilized methane for the whole mining sector. The E-PRTR database is based on the complete methane emission data (ventilation air methane plus the amount of not utilized methane) emitted directly from individual facilities and fronts.

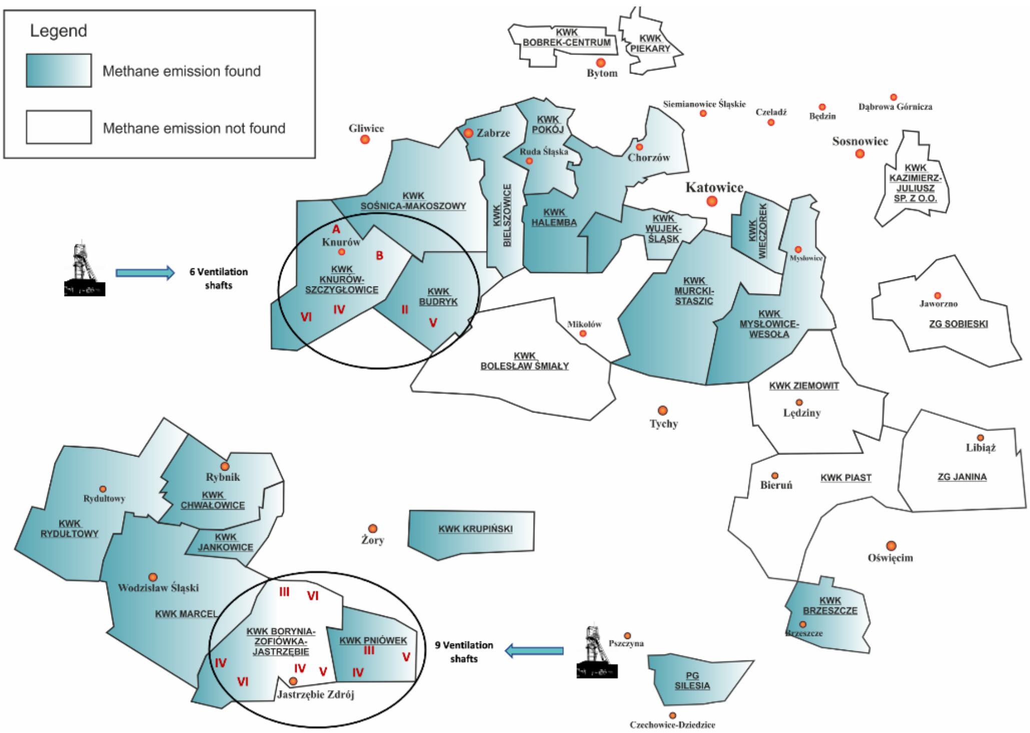

Figure 2. Map of mining areas of Upper Silesia Coal Basin with the indication of the mines with verified methane release. Also, the underground coal mines in the case study and their ventilation shafts are marked. State as of 2018.

Table 1. State of methane emission from Polish underground coal mines from 2013 to 2018 (WUG, 2019)

	2013	**2014**	**2015**	**2016**	**2017**	**2018**
Total methane bearing capacity, kt yr^{-1}	615.40	638.92	668.96	669.53	680.07	656.84
Ventilation air methane, kt yr^{-1}	417.08	408.76	425.90	424. 5	438.45	429.55
Drained methane, kt yr^{-1}	198.32	230.16	243.06	245.29	241.63	227.29
Amount of utilized methane, kt yr^{-1}	134,.8	151.57	141.32	139.82	152.00	145.62
Atmospheric methane emission, kt yr^{-1}	480.82	487.34	527.64	529.72	528.07	511.22
Drainage efficiency	**32%**	**36%**	**36%**	**37%**	**36%**	**35%**
Percentage of methane released to the atmosphere[a]	**78%**	**76%**	**79%**	**79%**	**78%**	**78%**
Coal output, Mt yr^{-1}	76.50	72.50	72.20	70.40	65.50	63.40
Specific methane emission, m^3 t^{-1}	11.10	12.30	12.90	13.30	14.50	14.40

a – including the methane captured by the drainage system but unused and subsequently released

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2.1 Sources of methane emission in the area of USCB

Hard coal is a sedimentary rock of biogenic origin, containing 75-90 % of elementary carbon carbonized mainly from plant debris in the absence of oxygen. The reason for that is diagenesis, transforming the organic substances into peat and then lignite and further its carbonification (metamorphism) into hard coal and anthracite (Kotarba 1998, Czapliński 1994; Szlązak et al. 2015).

The extraction of coal deposits is accompanied by gas emissions, including methane, carbon dioxide, higher hydrocarbons, nitrogen, and water vapor. The released mine gas typically contains more than 86% of CH_4 (Szlazak et al., 2015). The number of Polish mines in which CH_4 hazards to safe working conditions occur is steadily increasing due to mining at deeper levels and continuous extraction of deposits with high methane content (Swolkień, 2020; Szlazak et al., 2014). The last parameter, in contrast to specific methane emission, defines the volume of natural methane included in one tonne of dry ash-free coal without ash and moisture content (tonne daf) is determined in coal deposits in accordance with the normal standard PN-G-44200 (Szlazak et al., 2013). Its estimation for particular coal deposits allows forecasting of total methane emission for specific mining excavations, which is the basis for designing ventilation and methane drainage systems to maintain safe working conditions for mining crews.

The methane content in USCB varies a lot and can change within the whole USCB area and even within one deposit of a given coal mine (Dreger, Kędzior, 2021). Additionally, it increases with depth (Kotas, 1994; Tarnowski, 1989; Dreger, Kędzior, 2021). As an example, Figure 3a shows the variability of methane content in the Brzeszcze coal mine deposit. Methane content measurements were made following the procedure PN-G-44200 (Szlazak et al., 2013) in selected places in the excavations (white dots marked in the diagram). Then the methane content isoline map was constructed in a two-dimensional system based on the obtained results. Additionally, the map shows geological disturbances in the form of faults and anticlines, which can significantly increase the value of methane content in the deposit. It can vary between 4 to even 16 m^3 CH_4 t^{-1} daf and its increased values are visible in places of geological disturbance. Figure 3b, on the other hand, shows the distribution of methane content with depth in the from of frame plot for the individual depth intervals in Rydułtowy coal mine. It is visible that with the depth of -1000 m below msl (level 1200 m), the average methane content increases to 5.0 m^3 CH_4 t^{-1} daf, with determined methane content being in the range from 1.5 to 11.4 m^3 CH_4 t^{-1} daf.

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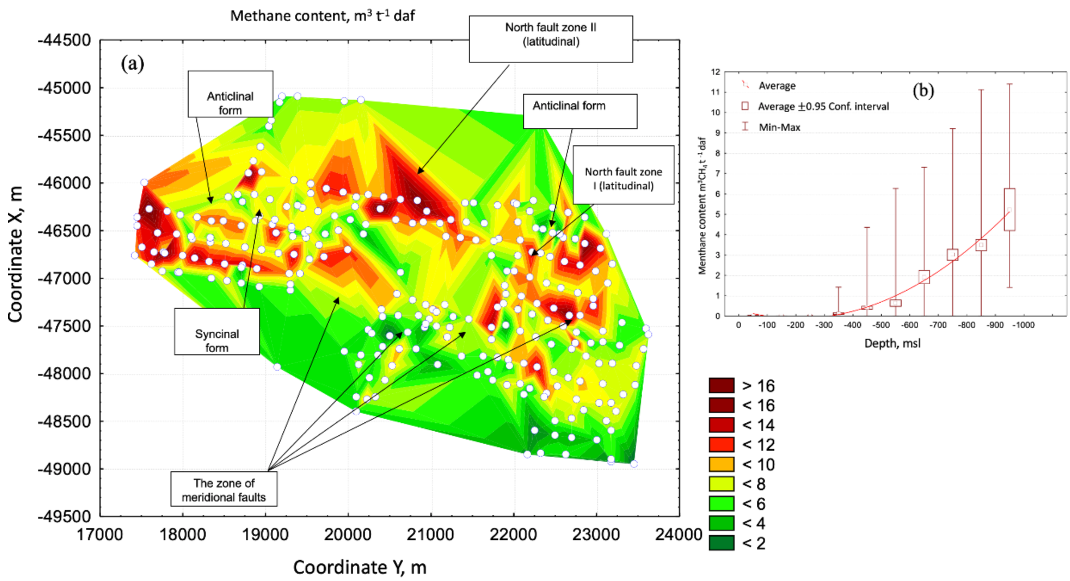

Figure 3. Methane content changeability with depth and across the deposit. (3a) Wafer chart of the methane content isolines within the deposit 352 in Brzeszcze coal mine in two-dimensional space with marked disturbances in the geological structure. White dots indicate methane content measurements points. The disorders observed based on the geological structure of the deposit are described in square boxes. X and Y are the coordinates. (3b) Frame chart of methane content changeability in individual depth intervals in Redułtowy coal mine. The mean values are marked as a midpoint. In the graph, the box corresponds to the range of results from 25% to 75%, and the whiskers to the minimum and maximum values.

Currently, the extraction of coal in Polish coal mines occurs on average at a depth of 800 meters below msl. However, in many of them, extraction is conducted at depths larger than 1000 m below msl. As a result, the deeper the coal mines go into the exploitation, the greater the amount of released methane. This is reflected in the data of WUG, presented in Table 1, which shows that, despite the decreasing number of active underground coal mines in Poland and reduced coal output, the specific methane emission have kept increasing between 2013 and 2018 (see Table 1).

2.2 Methods of methane capture

For the sake of safety of mining crews working underground, hard coal mines both in Poland and worldwide are required to introduce methane prevention methods (Journal of Laws 2017, item 1118) to ensure adequately low concentrations of methane in mining excavations. Depending on the forecasted total methane emission, active ventilation systems are used, and can in some cases be accompanied by a drainage system. Both of these installations must be designed specifically for a particular excavation site (longwall). Proper ventilation involves supplying a sufficient amount of air to each excavation in the mine to guarantee safe CH_4 concentration, i.e. lower than 2 % (Journal of Laws 2017, item 1118). Very often, low CH_4 emission makes conducting drainage technically challenging and economically unfeasible (Swolkień, 2020). This usually occurs when the forecasted total methane emission for

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the particular longwall is below 10 m^3 min^{-1} (Swolkień, 2020). In that case, CH_4 is removed directly into the atmosphere using a ventilation system, only. When the longwall emissions are above 10 m^3 min^{-1}, the air supply to the excavation is generally insufficient to reduce CH_4 concentration to the safe level. In such case, the coal mines are obligated to employ the second method, i.e., methane drainage (Journal of Laws 2017, item 1118). A properly designed drainage system reduces the ventilation air methane in excavations and the frequency of methane inflows into operating areas. It also prevents or reduces events such as outflows and abrupt outbursts of methane and rocks.

Hard coal mines around the world use different methods of methane drainage. One of the most widespread, pre-mining methane drainage, is mainly used in the United States and Australia (Kissel, 2006; Daimond, 1994; Fields et al., 1973; USEPA, 2009; Schatzel et al., 2008; Black, Aziz, 2009). It involves capturing methane for up to several years before coal extraction operations begin. Mining methane drainage, used mainly in Poland, Ukraine, and Russia has been described in numerous publications (Leisle, Kovalski, 2017; Shirin et al., 2011; Szlązak, Swolkień, Borowski, 2014, Szlązak, Swolkień, Obracaj 2014; Szlązak et al., 2015; Swolkień 2015). While specific applications differ from country to country, the general principle of methane capturing consists of draining it from the rock-mass and isolated goafs through specially designed boreholes. Then the gas is discharged via a separate system of pipelines on the surface, using the low pressure generated in a methane drainage station. Parameters and placement of the drainage boreholes are dependent on the ventilation system and local conditions related to geology and mining activities. The decisive factor that determines the level of methane capture and, therefore, the efficiency of methane drainage is the large number of boreholes simultaneously connected to the drainage system with negative pressure (in front of and behind the face). In other words, a drainage system that can ensure high efficiency of methane capture will cause a decrease in its emission to the excavation and then to the ventilation shaft.

Worldwide, currently implemented technologies enable capturing methane from particular longwalls with an efficiency of between 70 % to 80 %, depending on the forecasted total methane emission (Daimond, 1994; Fields et al., 1973; USEPA, 2009; Swolkień, Szlazak, Obracaj, 2014; Szlązak et al., 2015). That, in turn, means that between 20 % to 30 % of methane is still released as ventilation air methane (VAM). At present, the total drainage efficiency of capturing CH_4 in Poland with the methane drainage system is on average 35 % (see Table 1). The remaining 65 % is directly released into the atmosphere through ventilation shafts.

The coal mine facilities in Poland utilize drained methane either for own use, or sell it to external power plants (Szlązak et al., 2014; Swolkień 2015). The operation of the vast majority of such plants is based on internal combustion engines with pistons because of their high efficiency and relatively small investments needed. It is noteworthy that the most of the captured methane is utilized almost exclusively in winter (during the heating season). In summer, it is most often released into the atmosphere or flared. Unfortunately, data specifying the percentage of methane being processed by each of these methods are not publicly available.

The average methane utilization efficiency in Polish coal mines, computed for drained methane, is about 63 %, which means that 37 % of methane captured in the drainage system is still released from the coal mine drainage station that is (most often) located inside the primary mine compound on the surface. Therefore coal mine drainage stations should be treated as additional methane emission point sources characterized by non-negligible emissions, as the amount of methane emitted from them reach 13% of total annual emissions on average (see Table 1).

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In order to assess the variability of that average on facility level, we have obtained data on the annual utilization of drained gas in a subset of mines targeted during the CoMet 1.0 (see section 3). Over the whole 2018, the efficiency of drained methane utilization for all the facilities in JSW S.A. company reached 57%, of which 75% was sold to external power plants, 24% burned in gas engines, and about 1% used in gas boilers (Szlązak, Swolkień, 2021). The highest consumption of drained methane, reaching 83%, was achieved by the Zofiówka, Borynia, and Pniówek facilities. On the contrary, the least methane was utilized in Szczygłowice (5%) and Budryk (40%). In the case of Knurów, all (100%) drained methane was released into the atmosphere.

These examples show that utilization of drained methane is highly variable, and when emissions from global databases are disaggregated using average estimates, large errors can occur on facility level. Unfortunately, data about the utilization of drained methane is proprietary and not publicly available. Until such information is widely released, any efforts for quantification of methane emitted from drainage installation, will have limited accuracy and precision. Attempting to estimate emissions on sub-annual temporal scales will be even more challenging, as the high-frequency monitoring data is either hard to obtain, or even sometimes nonexistent.

Comparing the atmospheric methane emission from the USCB mining areas in Poland with other mining regions of the world requires recognizing the prevailing mining and geological conditions and the methane drainage methods used (Swolkień, 2020). The considerations presented in this work concern mining areas where exploration is carried out at significant depths, and the rock mass is characterized by high methane content increasing with depth (see Fig. 3a, b), low permeability, and high ground stress (Szlązak et al., 2012; Roszkowski, Szlązak 1999; Szlązak et al., 2015; Szlązak, Borowski 2006). A similar situation occurs in most of coal mines in Ukraine, Russia and China (Zahai et al., 2008; Romeo, 2013; Younn et al., 2012; Boger et al., 2014; Szlazak et al., 2012). The shallower coal deposits are characterized by higher permeability, as a result of which it is possible to apply the pre-mining drainage (Karacan et al., 2011; Greedy, Tilley, 2003). Ideal conditions occur in mines located in the United States, though Australia uses this technique as well (Kissel, 2006; Daimond, 1994; Fields et al., 1973; USEPA, 2009; Schatzel et al., 2008; Black, Aziz, 2009).

The considerations presented above show that the atmospheric methane emissions are associated with the activities of underground coal mines. Because as of 2019, Germany closed its coal mines, and the Czech Republic will do so by the end of 2022, the USCB in Poland was the best place to conduct measurements during the CoMet mission.

3 USCB as a case study for CoMet 1.0 mission

Because USCB is an area of highly concentrated CH_4 emissions and is ideal for comparing all scales of surveys: ground-based, airborne, and satellite. The measurements carried during the pre-campaign in 2017 (CoMet 0.5) were the first attempt to observe the temporal emissions of CH_4 directly from the source (Swolkień, 2020; Andersen et al., 2021). Till then, only ground-based measurements were carried out around the shafts (Nęcki et al., 2017). The lack of information about specific temporal concentrations and about the factors that influence them is a significant shortcoming for a validation of actual emission rates from aircraft measurements (in-situ, remote sensing). Collected

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data during the pre-campaign were also beneficial for planning and prioritizing mines in the USCB for the primary CoMet 1.0 mission, which took place from May 14 to June 13, 2018 (Swolkień, 2020; Kostinek et al., 2020; Fiehn et al., 2020; Luther et al., 2019; Krautwurst et al., 2021). Based on that prepatory study seven coal mines facilities with 15 ventilation shafts in Upper Silesia have been prioritized for the investigation within CoMet 1.0. Figure 2 presents the map of the mining areas of the Upper Silesia Coal Basin with the indication of those mines with verified methane release and also ventilation shafts.

The CoMet 1.0 campaign, along with the observations and tests conducted from aircraft and ground, performed measurements of methane concentrations directly in the ventilation shafts of selected individual coal mine facilities. The research included all coal mines that belong to JSW SA company in an area covering approximately 195,3 km^2:

- Coal mine Pniówek – three ventilation shafts
- Combined entity Zofiówka-Borynia-Jastrzębie, consisting of three individual facilities – six ventilation shafts
- Coal mine Budryk – two ventilation shafts
- Combined entity Knurów-Szczygłowice, consisting of two individual facilities – four ventilation shafts

JSW S.A. is the largest coking coal producer in the European Union and one of the leading producers of coke, an essential ingredient for steel production. In 2018 its coal mines released 237,77 kt of CH_4 into the atmosphere and were responsible for 16 % of total atmospheric emissions from the underground sector in Europe. The advantage of including these mines to the mission targets is their localization and the fact that they are the most methane-prone.

4 The methodology of methane concentration and emission measurements

According to the regulation (Directive 2003/87/EC December 19, 2018; Journal of Laws 2016 item 1877), all industrial companies in Poland, including coal mines, must report greenhouse gas emissions to the National Centre for Emissions Management (KOBiZE- IOŚ-PIB). KOBiZE was created to carry out commitments resulting from the EU Directives and the EU Emission Trading System (EU ETS). Additionally, coal mines are obligated to report the emissions for the National Pollutant Release and Transfer Register (The Environmental Protection Low of April 27, 2007, art. 236a) each year.

The traditional approach to determine pure methane flow in a mine airway employs is based on a combination of measurements and calculation methods, most frequently using airflow velocity (measured with a handheld anemometer) with the collection of air samples, subsequently analysed for methane concentrations in the laboratory. The procedure is carried out by a trained employee authorized by the coal mine operations manager. For sampling, either special vacuum bottles ("Gresham tubes") or standarized sampling bags are used. These measurements are usually taken in the return airways, near the point where the return intersects with the ventilation shaft. In some cases, multiple returns are leading to a single ventilation shaft. In such a case, the total air flow rate will be the sum of the air flow measurements from all returns leading to the shaft. The methane concentration will be the weighted average of the methane concentration readings in each return. The calculated amount of methane relates to actual conditions that are present in the shaft. The methane flow rate Q_{CH4} is then calculated according to:.

$$Q_{CH4} = Q_{air} \cdot {}^{c_{CH4}}/_{100} \quad (1)$$

where c_{CH4} is methane concentration (in %), and Q_{air} is the air flux in in m^3 CH_4 min^{-1}. The measurement is only performed at a limited frequency for the purpose of annual reporting.

High frequency (up to hourly) emission data could be a helpful tool to measure methane concentration in coal mine shafts. All coal mines, including ones described in the paper, are obligated to use the fire teletransmission monitoring system (SMP-NT/A) system to monitor safety parameters. Although it also measures methane concentrations, it is rarely used by coal mine operators to estimate ventilation shaft methane emissions. Only the Pniówek coal mine uses it to report it, and the remaining mines use traditional measurements, as described earlier.

According to Polish mining regulations (Journal of Laws 2017 item 1118), all coal mines are equipped with the methane fire teletransmission monitoring system. The most widely used system in Polish coal mines is SMP-NT/A (acronym from Polish: "System Metanowo Pożarowy") with integrated CMC-3MS telemetry panels (the type of CTM -acronym from Polish: "Centrala TeleMetryczna") (Wojaczek, Wojaczek, 2017; emagserwis.pl; Wasilewski, 2012; Swolkień, Szlązak, 2021). The monitoring system is usually equipped with sensors to measure inter alia the methane concentration, carbon monoxide, oxygen, air velocity, temperature, and pressure. An intrinsically secure telecommunication network allows sending data to and from the sensors to the telemetry panels.

Figure 4 schematically displays the methane fire teletransmission sytem (Wojaczek, Wojaczek, 2017). In such systems, each methane sensor with continuous recording protects all ongoing faces, longwalls, and ventilation shafts and is most often connected directly to a telemetry panel (CTM). Other sensors (e.g. CO_2, O_2), due to lower electricity consumption, can be connected to underground pit stations (SD). The underground station is powered by a transmission line from the CTM switchboard located on the surface. Contemporary environmental parameter control systems are used not only to monitor hazards (methane and other ventilation parameters), but most of all they perform safety-related functions, such as: switching off electricity in the endangered area in the event of exceeding sensor threshold settings, displaying and local alarming in the place where the sensor is installed about exceeding the threshold settings (Wojaczek, Wojaczek, 2017).

The methane measuring apparatus consists of a DCH recording sensor (type MM-4), shown in Figure 4, (emagservice.pl; Swolkień 2020). Using two independent elements, like a pellistor gas detector for a CH_4 concentration range of 0–5% (low concentration range) and a conductivity bridge for a CH_4 concentration range of 5–100 % (high concentration range), enables continuous monitoring of CH_4 concentration in the air (emagserwis.pl). Sensors can switch automatically, and their head can be placed on the cover or through an up to 30-m long cable. A replaceable filter protects the air inlet to the sensor head. The sensor response time is less than 6 seconds and it can operate in the temperature range from -10 ºC to 40 ºC and humidity in the range from 0 to 95 % RH (relative humidity). The sensor has a resolution of 0.1 %. The relative uncertainty of measurements is equal to 0.1 % for the low concentration range, and for the higher concentration range, it is 3 % (emagserwis.pl).

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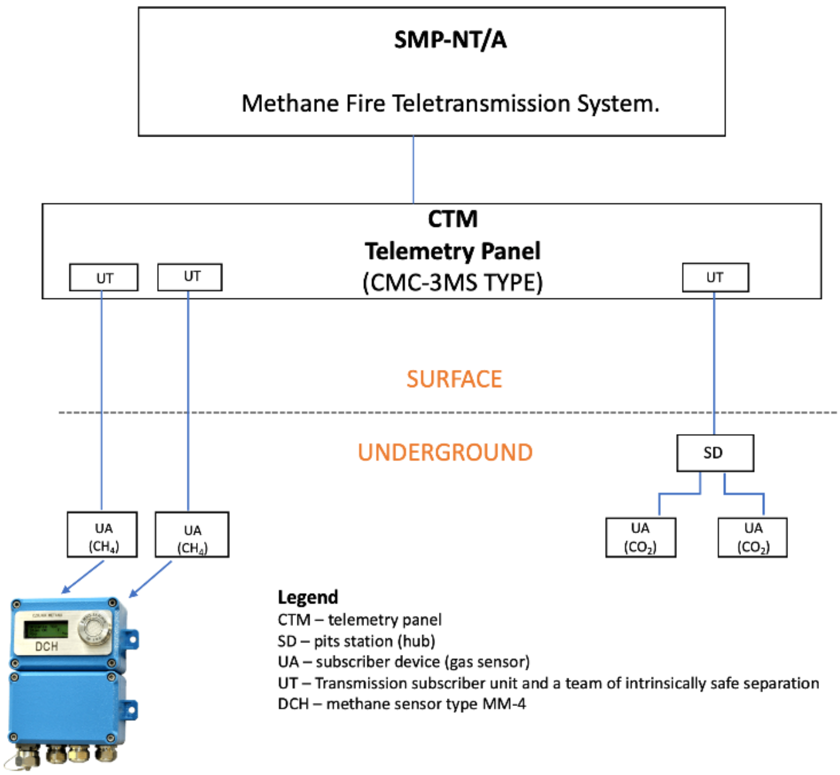

Figure 4. Block diagram of a system for monitoring environmental parameters with a star-shaped structure of the teletransmission network, commonly used in Polish coal mines, including commonly used methane sensor type MM-4 (production EMAG Serwis sp. z o.o.; emagserwis.pl)

The conditions that methane sensors have to fulfill and their maintenance and calibration methods are described in the European standard IEC 60079-0:2013-03. This regulation gives guidance and recommends practice for the selection, installation, safe use, and care of electrically operated Group II equipment intended for use in industrial and commercial safety applications and Group I equipment in underground coal mines for the detection and measurement of flammable gases (PN-EN 60079-0:2013-03; PN-EN IEC 60079-0:2018-09).

Calibration of the measurement sensors in the ventilation shafts is conducted in two steps:

- once in a week with the mixture of 2.2 % of methane for low concentration range (0-5 %),
- every two weeks for a higher concentration range with a blend of 70 % methane (0-100 %).

Figure 5 presents the ventilation shaft scheme, with measuring sensor locations indicated with black coloured dots. Methane sensors are placed approximately 10–15 m below the inlets to the ventilation channel. The air temperature in the shaft is approximately 18 to 20 °C, and the height of the ventilation tower is about 10 to 15 meters.

According to Polish mining regulations (Journal of Laws 2017 item 1118), the methane concentration in the joint exhaust air must not exceed 0.75 %, and the corresponding measurements have to be performed in the ventilation shaft in the joint return airflow, not less than 10 m:

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- below the channel of the main fan (see Fig. 5 – black dot),
- above the highest return air inlet, which flows from the excavations to the ventilation shaft.

Additionally, stations of the main fan should be equipped with instruments that perform continuous measurements of:

- the static air pressure in the ventilation channel in front of and behind the main valve (see Fig 5. – red dots),
- the air velocity in the ventilation channel (see Fig.5 – blue dot),
- the static air pressure in the cross-section of the exhaust shaft below the ventilation channel.

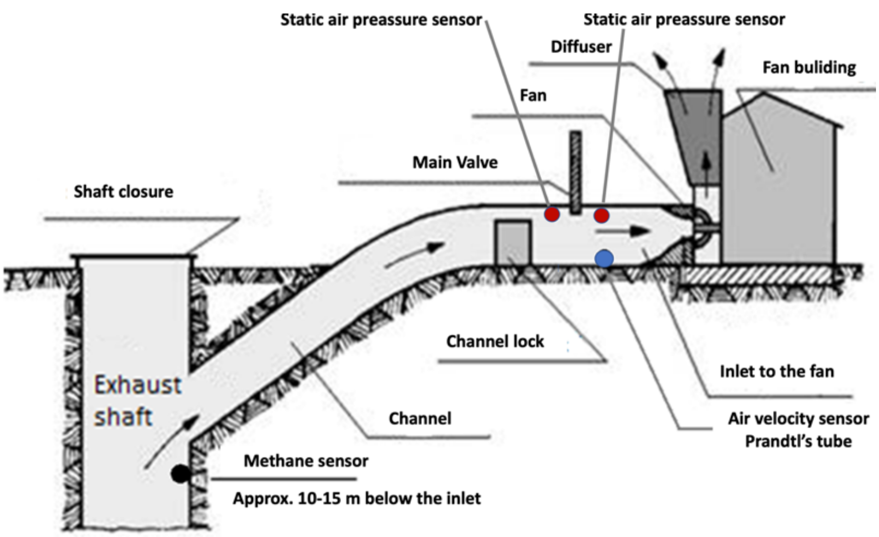

Figure 5. Typical ventilation shaft scheme. Methane, velocity, and static pressure sensors are marked with color dots. Following Swolkień 2020. The original Figure was published under a Creative Commons Attribution 4.0 International 225 License, http://creativecommons.org/licenses/by/4.0/.

It should be noted that fan stations and the diffusers are made individually for each coal mine, depending on the scope of mining works performed, and the magnitude of air flux supplied to the appropriate mining areas. Nevertheless, the general principle of their construction is similar for all coal mines. Figure 6a & b, show an example of a diffuser (Bogdanka coal mine, www.stalkowent.pl).

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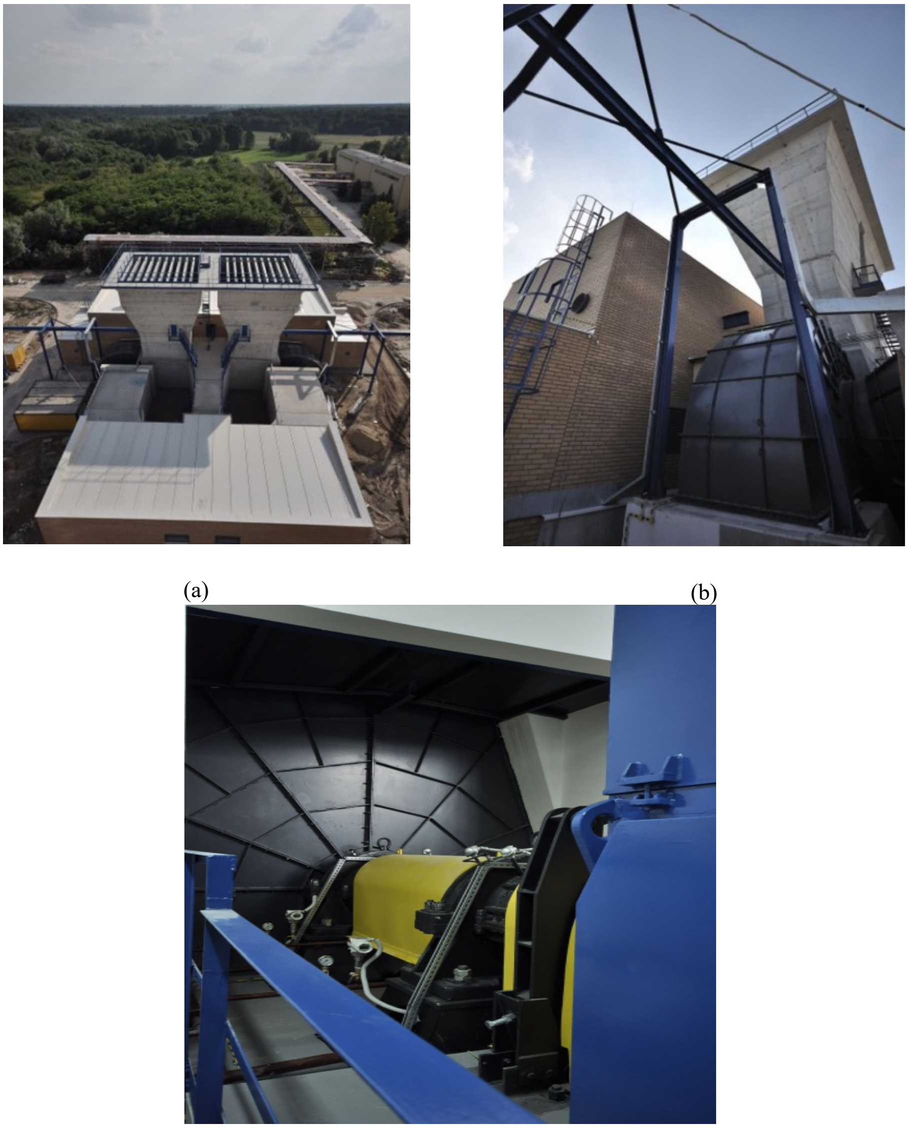

(a) (b)

(c)

Figure 6. Photographs of the fan station with diffuser in Bogdanka coal mine build by Stalkowent sp. z o.o: (a) Fan station with a diffuser – view from above; (b) Photograph of the channel lock, main valve, and the diffuser; (c) Main valve and fan, (www.stalkowent.pl)

In order to measure methane flow rate, it is necessary to measure the air velocity in the ventilation channel, which is done using a Prandtl tube installed between the main valve and a fan (see Figure 5 – blue dot) and connected with a manometer measuring and continuously recording dynamic pressure (Swolkień 2020). The air flow rate through a ventilation channel is given by

$$Q_{air} = A_{ch} \cdot v_{ch} \quad (2)$$

where Q_{air} is the resulting air flow rate (in m^3 min^{-1}), A_{ch} is the channel cross-section (in m^2) and v_{ch} is the air velocity (in m s^{-1}) measured as described above. The methane flow rate (in m^{3}CH$_4$ min^{-1}) is then calculated by

$$Q_{CH4} = 0.95 \cdot Q_{air} \cdot {c_{CH4}}/{100} \quad (3)$$

where c_{CH4} is methane concentration (in %). The index 0.95 results from the fact that 5% of the air discharged through the shaft comes from the shaft closure (see Fig. 5), which must be taken into account when calculating the methane flow rate. Next step is the conversion into methane emission rate which is done by

$$m_{CH4} = Q_{CH4} \cdot \rho \quad (4)$$

where ρ is methane density (0.717 kg m^{-3}) referred to normal conditions.

Regardless of the adopted methodology of measuring the total methane emissions from individual coal mine facilities (STMP-NT/A, or traditional methodology), the amount of methane released from the ventilanion shafts is always increased by the amount of methane blown out to the atmosphere at the methane drainage station. The last parameter is measured using the thermal flow meter installed in the discharge pipeline and by measuring methane concentration with a chromatograph.

The relative uncertainty of the air flow rate measurements usually amounts to ~10 % and for methane concentration ~0.1%. Harsh conditions existing in the ventilation shaft, meaning high humidity, waterlogging, often cause the measurement to operate outside of the nominal operating range in the shaft. Considering that, we estimate the overall methane flux uncertainty calculated with this method to be higher then that simply stemming from respective instrument uncertainties. We consider 20 % as an aprropriate conservative estimate.

The analyzes of the coefficients influencing the variability of methane emissions presented in the article were made based on instantaneous measurements of methane concentrations using the methane fire teletransmission monitoring system (SMP-NT/A) and methane sensors installed in the ventilation shafts of the studied mines (see Fig. 5).

5 Factors that influence the methane emission from coal mines

5.1. Results from in-stack measurements

Figures 7 and 8a depict variations in the concentration and methane fluxes in the selected 15 ventilation shafts under study in the period from May 14 to June 13, 2018, based an hourly values. Additionally, Figure 8b presents an overview of the average air flow rates for each ventilation shaft. All temporal data for individual shafts of selected coal mine facilities presented below, together with emission data from State Mining Authority (WUG, 2019*)* and E-PRTR (E-PRTR*)*, were compiled by the CoMet team in the form of an internal dataset called CoMet v4.0 (CoMet ED v4, 2021). Additional results of statistical description of concentration and flow rates variation are presented in Tables 2 and 3.

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The analysis of data presented in Figure 7 and Table 1 shows that the highest average values of methane concentrations were recorded for Budryk V (0.40 %), followed by Pniówek IV (0.26 %).The lowest values, on the other hand, were observed at Knurów Bojków V, Borynia III, and Jastrzębie IV shafts. We find a striking variability of concentration in mantioned shafts. Despite the low average concentration, the highest recorded values reached up to 0.13 % at Borynia III and 0.30 % for Knurów Bojków V. Similarly, in Budryk II and Pniówek, V concentrations varied between 0 and 0.46 %. It should be noted that in Borynia VI, the average from May 17th to 30, methane sensors displayed zero concentration which is impossible since this shaft is responsible for ventilating the main mining areas of the mine. According to the source file, it had a malfunction during the indicated period. This period was then excluded from further calculations.

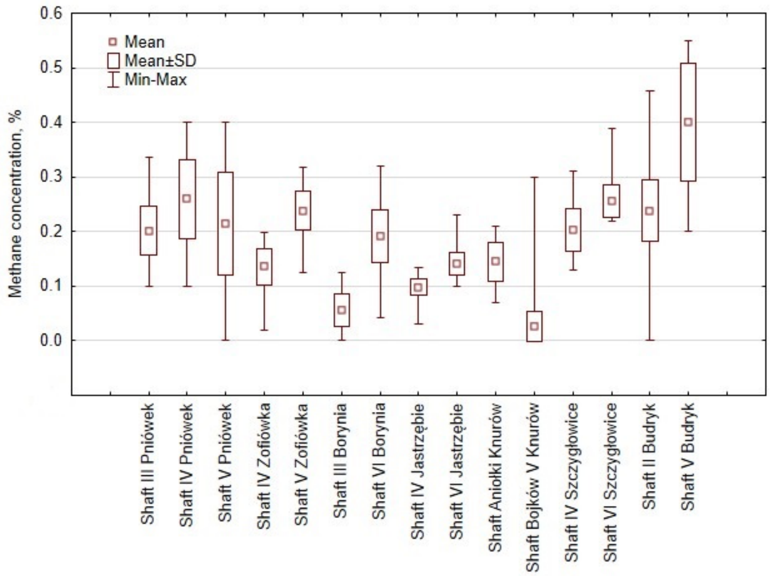

Figure 7. Average methane concentration and variation in the investigated shafts within the observation period from May 14 to June 13, 2018

Table 2. The statistical description of methane concentration variation in ventilation shafts understudy

Statistical description (CH_4 concentration variation), %						
Name of the shaft	Average	Median	Min.	Max.	Standard deviation	**Frequency of concentration data**
Shaft III Pniówek	0.20	0.20	0.10	0.34	0.05	hourly
Shaft IV Pniówek	0.26	0.30	0.10	0.40	0.07	hourly
Shaft V Pniówek	0.22	0.20	0.00	0.40	0.09	hourly
Shaft IV Zofiówka	0.14	0.14	0.02	0.20	0.03	hourly
Shaft V Zofiówka	0.24	0.24	0.13	0.32	0.04	hourly
Shaft III Borynia	0.06	0.04	0.00	0.13	0.03	hourly

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Shaft VI Borynia	0.19	0.17	0.04	0.32	0.05	hourly
Shaft IV Jastrzębie	0.10	0.10	0.03	0.14	0.02	hourly
Shaft VI Jastrzębie	0.14	0.15	0.10	0.23	0.02	hourly
Shaft Aniołki Knurów	0.15	0.14	0.07	0.21	0.04	hourly
Shaft Bojków V Knurów	0.03	0.02	0.01	0.30	0.03	hourly
Shaft IV Szczygłowice	0.20	0.21	0.13	0.31	0.04	daily average
Shaft VI Szczygłowice	0.26	0.25	0.22	0.39	0.03	daily average
Shaft II Budryk	0.24	0.25	0.00	0.46	0.06	hourly
Shaft V Budryk	0.40	0.45	0.20	0.55	0.11	hourly

The data presented above show that in none of the monitored ventilation shafts, the maximum permissible value of methane concentration of 0.75% was exceeded (Journal of Laws 2017 item 1118). Nevertheless, because of the high temporary variability of methane concentrations in individual shafts, their instantaneous values were 1.68 (Borynia VI) and 1.91 (Budryk II) times higher than the average for the analyzed period, in the case of Knurów Bojków V, even higher. This is important from the point of view of verifying measurement data obtained from measuring devices installed onboard aircraft.

The data presented in Figure 8b reveal that the average values of air flux in the shafts ranged from 6000 m^3 min^{-1} for Knurów Aniołki to over 23000 m^3 min^{-1} Zofiówka IV. It is crucial to remember that the air flux for each ventilation shaft is set based on the number of longwalls under operation in a given facility, in order to maintain safe operating conditions underground.

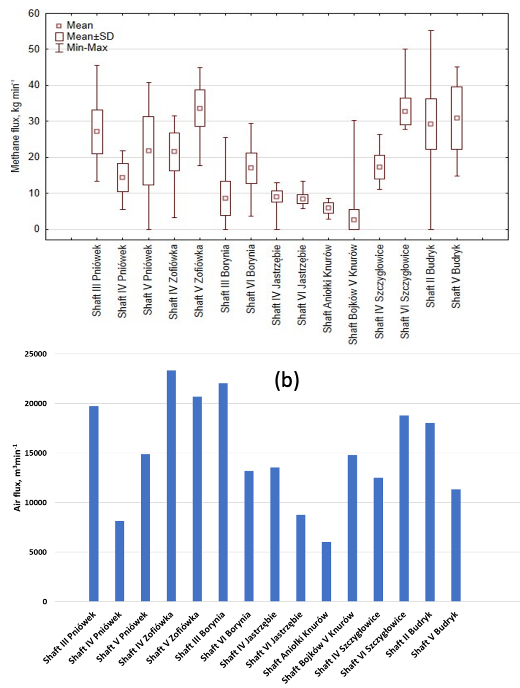

Figure 8. Diagram of methane flux variation (8a) and average values of air flux (8b) in shafts under study

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Table 3. The statistical description of methane fluxes variation in ventilation shafts understudy

Statistical description (CH_4 flux variation), kg min^{-1}							
Name of the shaft	**Average**	**Median**	**Min.**	**Max.**	**Standard deviation**	**Frequency of air flux data**
Shaft III Pniówek	27.08	26.84	13.42	45.54	6.08	hourly
Shaft IV Pniówek	14.32	15.94	5.52	21.80	3.93	hourly
Shaft V Pniówek	21.79	20.43	0.00	40.87	9.50	hourly
Shaft IV Zofiówka	21.51	22.50	3.18	31.50	5.29	monthly average
Shaft V Zofiówka	33.64	33.86	17.67	44.88	5.07	monthly average
Shaft III Borynia	8.59	5.94	0.00	25.49	4.75	hourly
Shaft VI Borynia	16.98	16.78	3.56	29.51	4.24	hourly
Shaft IV Jastrzębie	9.09	8.97	0.00	12.88	1.59	hourly
Shaft VI Jastrzębie	8.38	8.85	5.78	13.43	1.28	hourly
Shaft Aniołki Knurów	5.93	5.70	2.84	8.58	1.45	monthly average
Shaft Bojków V Knurów	2.61	2.02	1.01	30.24	2.77	monthly average
Shaft IV Szczygłowice	17.27	17.51	11.01	26.34	3.26	daily average
Shaft VI Szczygłowice	32.71	32.18	27.85	50.01	3.67	daily average
Shaft II Budryk	29.29	30.28	0.00	55.35	7.03	daily average
Shaft V Budryk	30.98	33.34	14.82	45.18	8.67	daily average

When it comes to methane fluxes, the variability of concentration transfers to the fluxes and is most visible in Budryk II and V, Knurów Bojków V, Borynia III, and also Pniówek V (see Fig. 8a). The maximum flux for Knurów Bojków V was 11.60 times the average value and for Borynia III almost 3 times. The largest amount of methane was released from Zofiówka V, Szczygłowice VI, then Budryk V and II and the least from Knurów Bojków V and Knurów Aniołki (see Table 3).

Obviously, the higher the air flux is, the more diluted the gas. It is visible when one compares the methane concentration and fluxes in both shafts. The values of methane concentration were more or less the same, 0.15 % for Knurów Aniołki and 0.14 % for Zofiówka IV, respectively (see Table 2), while flux in the second-mentioned shaft was 3.6 times the one from Knurów Aniołki (see Table 3 and Figure 8b). A similar situation existed also in Budryk V, characterized by the highest concentration of all shafts, 0.40 % (see Table 2), but releasing less methane than Zofiówka V and Szczygłowice VI (see Table 3).

5.2. Tentative reasons for the findings

Large fluctuations in methane concentrations and fluxes presented in Figures 7 and 8a can be explained by the release of methane from rock mass during the mining operation. The rock mass is a porous medium, and the methane flows through interconnected spaces and channels or tiny fractures due to the filtration process. In fact, in underground conditions, filtration occurs in a much more complex form since the coal seams are not only the rock through which the methane filters but also contain it in adsorbed form (Swolkień, 2015). The phenomena of desorption and simultaneous filtration are closely related, both mechanically and energetically.

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The methane migration feasibility depends on the permeability of the deposit and its saturation with methane (methane content-see Fig.3a & b), which means that variations in the composition and structure of rock mass influence the level of CH_4 concentration and its fluxes. Therefore, the rate of methane emission from the rock mass will depend on its permeability, and to a large extent, may vary depending on the analyzed mining region. The process of methane filtration from the coalbed to the excavation takes place as a result of rock depressurizing during the mining operation. This lowers the pressure of free gas, which contributes to its desorption.

In the condition of low permeability, emission of methane occurs only after the decompression of rock mass that happens after mining starts and strongly depends on the scope of works proceeded. It is the highest at the longwall face (between 0 and 20 meters) and decreases as the distance from the face increases. Then it stabilizes at a level corresponding to the conditions in an unextracted seam, and the emission of methane decreases. Based on that, methane can be emitted to mining excavations due to its desorption and gradual filtration under the pressure gradient caused by mining or as an effect of its outflow from fractures and cracks in the seam due to the mining operations (Szlązak et al. 2015). Regardless of one of the forms of methane outflow, its presence will always result from increased mining activities.

The fluctuating values recorded in the Pniówek V and IV coal mine shafts are striking evidence for the complexity of processes that accompany mining activity. Figure 9 presents the changes in methane concentration in those shafts during the observation period. The vast majority of recorded results are within the range from 0.10 to 0.40 %. In shaft V, the concentration values ranged from 0.10 to 0.40 % during the first half of the research period. After May 31, a decrease was observed, with the recorded values ranging from above zero (except for ten cases in which zero values were identified) to 0.20 %. In the case of shaft IV, the values ranged from 0.10 to 0.30 % until May 18, then they dropped and maintained on the level 0.10 to 0.20 % till May 28. Afterwards, the range changed from 0.20 to 0.40 %. In the case of Shaft III, the values fluctuated between 0.10 to 0.20 %. This range shifted upwards (from 0.20 to 0.30 %) after June 8.

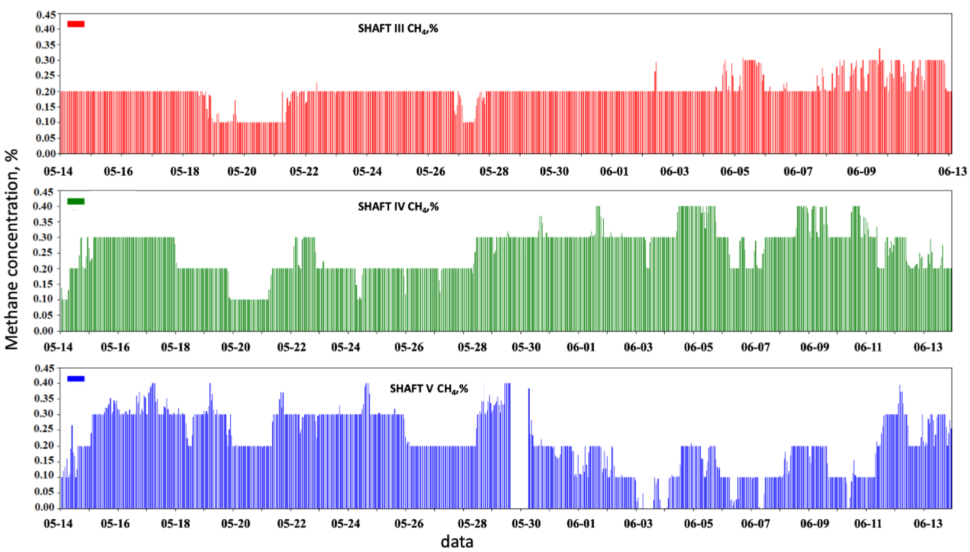

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Figure 9. Variability of hourly data of methane concentration in Pniówek V and IV coal mine facility in the period from May 14 to June 13, 2018.

The temporary decreases and increases in Pniówek shafts are linked to the current extent of mining activities, mainly the value of coal output. According to the private communication with the ventilation department at that time, the coal mine struggled with the exploitation of the high methane-prone longwall panels. In addition, due to the occurrence of methane exceedances in the underground atmosphere, there were multiple technological breaks and suspension of mining works. Therefore, we assume that decreased values in Shaft V were caused mainly by reduced mining activities in an individual section of the coal seam excavated at the time. In that case, the permeability of the rock mass decreased, which resulted in reduced inflow of methane into the underground air, which then reflected the level of gas concentration in the return air. Similarly, in shaft IV, between May 18 and 28, a decrease in concentration was connected with temporary downtime of mining works and reduction of output. After that time reappearing increase of methane concentration was cosed by preparing the new section of coal deposit for exploration. That resulted in the decompression of the rock mass and more methane to be released after a temporary concentration decline.

In addition to methane desorption, methane is also released due to its outflow from fractures and cracks in the rock mass due to mining operations. Instantaneous peaks in methane concentration in the individual ventilation shaft of Knurów Bojków V, presented in Figure 10, are an example of such situations. Despite the relatively low concentrations along the whole period (0.01 % to 0.04 %), there were two noticeable increases on June 2 and June 13 (see also Table 2). In the first case, the high concentration of 0.30 % had maintained for two hours and then dropped to 0.03 %. In the second case, it had reached 0.30 % and kept for over five hours. Then it dropped to 0.03 %. This situation resulted from an abrupt outflow of methane from fractures and cracks in the excavated seam that was ventilated via this shaft.

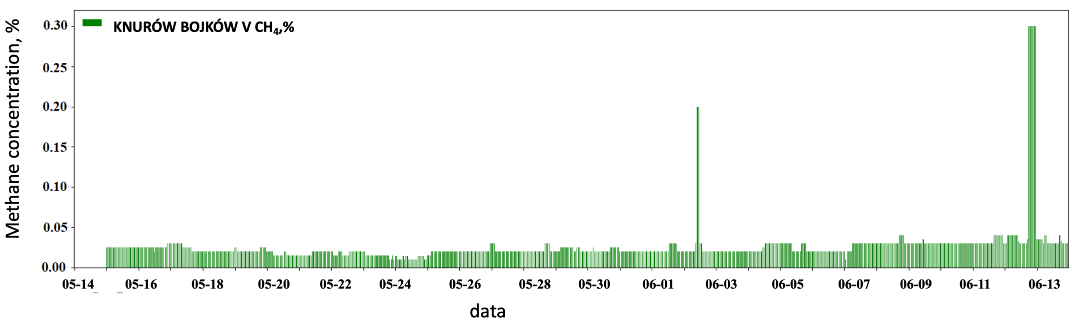

Figure 10. Variability of hourly data of methane concentration in Knurów Bojków V coal mine facility in the period from May 14 to June 13, 2018

Of all the shafts under analysis, the highest by far values of methane concentrations were reported for Budryk V (see Table 2). They ranged from 0.20 to 0.55 % and were subject to considerable fluctuation (σ = 0.11 %). The gathered data suggests a high methane content of the extracted longwall ventilated by the shaft in question. Although within

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required margins at all times, such high concentrations suggest that the airflow rate (~11300 m^3 min^{-1}; see Fig. 8b) and methane drainage method might not have been selected optimally during the studied period.

6 Inventory and temporal data comparison

The presented temporal data covering one month (from May 14, 2018, to June 13, 2018) revolve that individual coal mines discharged between 186.82 to 349.40 kg min^{-1} of methane (based on Fig. 11). The highest emission was recorded for Pniówek and Budryk facilities, and amounted to an average of 61.11 and 60.02 kg min^{-1}, respectively. Thus, during the month of observation, the analyzed coal mines released on average 390.92 kt of methane per day (see Fig.11). Assuming constant monthly emissions from each ventilation shaft, results in a yearly average emission of 142.68 kt yr^{-1}. This number is 27 % lower than the reported 197.82 kt yr^{-1} by WUG inventory (WUG, 2019). In the case of E-PRTR, the difference is even larger and reaches 36 % (CoMet ED v4, 2021), E-PRTR emissions again being higher. The main reason is that temporal data presented in this paper include only ventilation shafts emissions, excluding methane released from the drainage station (not utilized), which is included in the E-PRTR inventory.

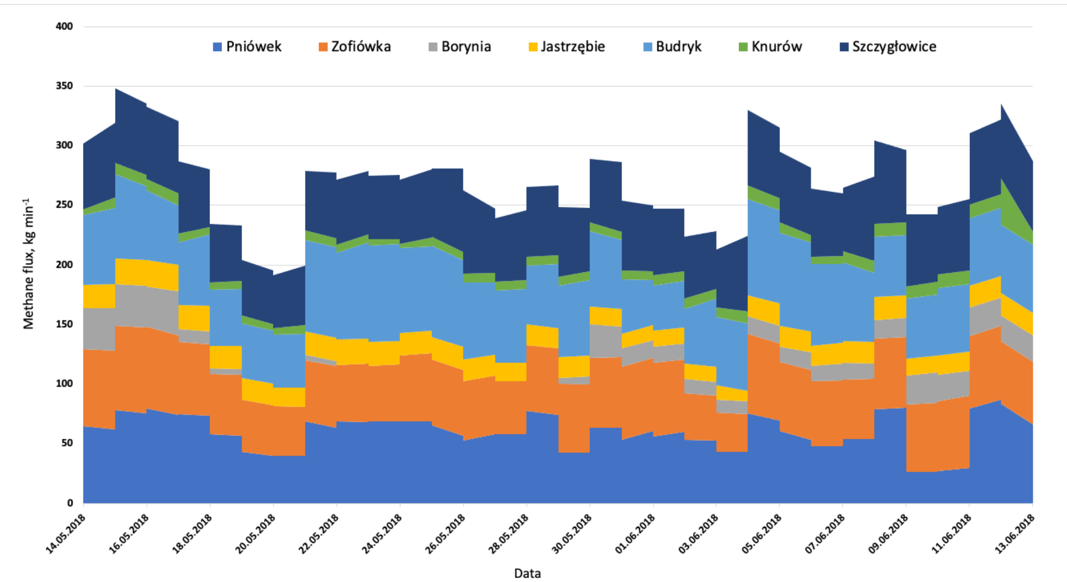

Figure 11. Summary of the methane amount discharged from individual coal mine facilities based on temporal data

The disadvantage of the bottom-up inventories such as E-PRTR and WUG is that those data refer to the entire coal mine facilities and not to individual ventilation shafts or methane drainage stations and are annual data. In the WUG register, for instance, annual methane emissions are reported for the coal mines as a whole (see Table 4), which means that in the case of combined entities such as Zofiówka-Borynia -Jastrzębie, and Knurów -Szczygłowice, only one value is given. The discrepancy between temporal data and WUG inventory for those coal mines ranges from 1 % to 5 %. This means that verifying measurement data based on, e.g. in-situ aircraft measurements using a mass balance or model-based approach on a regional scale (for the entire USCB region) with inventories gives quite good agreement

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(Fiehn et al., 2020; Kostinek et al., 2020). Nevertheless, serious problems arise on the local scale because this approach might underestimate or overestimate emissions from individual shafts. For example, in the CoMet v4.0 internal dataset for comparative purposes, data from the WUG and E-PRTR registers for individual coal mine facilities were divided evenly into each ventilation shaft due to the lack of temporal data. When comparing in-situ aircraft measurements using a model-based approach (Kostinek et al., 2020) with E-PRTR large variations between individual shafts have been found. For that reason, measurement data should preferably be compared with temporally resolved data from the origin of methane emissions.

Table 4. Comparison of temporal data from shafts with WUG and E-PRTR inventory

	Based on temporal data		E-PRTR	Discrepancy	WUG	Discrepancy
	kt yr^{-1}		kt yr^{-1}		kt yr^{-1}	
Pniówek	32.12		54.70	41 %	49.19	35 %
Zofiówka	28.99	47.10	27.80	4 %	46.42	1 %
Borynia	8.93		12.80	30 %		
Jastrzębie	9.18		8.10	13 %		
Budryk	31.54		78.40	60 %	66.14	52 %
Knurów	4.45	34.30	4.86	8 %	36.05	5 %
Szczygłowice	29.85		37.50	20 %		

Discrepancies in temporal data and both inventories are presented in Table 4 and result from several factors. The most important is the assumption that methane concentrations in the ventilation shafts are stable, which is not valid. They change across the year, a month, and even across a day (see Fig.11). Assuming their stability throughout the entire year, based on measurements from only one month leads to underestimating methane emissions like in Budryk, Pniówek, and Szczygłowice or overestimating like in Jastrzębie or Zofiówka (see Table 4). In Borynia, a high discrepancy is due to the malfunction of the methane sensor in Borynia VI between May 17 to 30 (according to the source file). Other reasons for disagreement are the methodology, frequency, and the time of measurements.

The most common methods for methane concentration measurements used in Polish coal mines are based on combining a handheld anemometer to measure airflow velocity with air samples taken for methane measurements using special vacuum bottles and analyzed in the laboratory (see chapter 3). Such measurements are required to meet statutory safety regulations and must be undertaken by a trained person in accordance with recognised procedures and can be used for methane emission monitoring provided they are taken during production shifts (UNECE, 2021). Nonetheless, these measurements are conducted only once a month, which means that the amount of released methane through the year is calculated based on twelve measurements, only. This can lead to differences between temporal data and inventories, like in the Budryk coal mine (see Table 4). The preferable way of measuring methane concentrations would be the usage of the methane fire teletransmission monitoring system (SMP/NT). However, it is aimed at

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checking that preset criteria are met whereas potential emission monitoring is aimed at quantifying gas flows with a high degree of precision; therefore before it usage it should be made fit to high-precision methane measurements. Additionally, if we look at the Pniówek coal mine (the only coal mine that uses a monitoring system to measure methane emissions), we see that even using methane fire teletransmission monitoring system can underestimate emissions when lacking an appropriate frequency of measurements. Recording the methane concentrations only once a month, considering their high variability (see Fig.9), does not provide reliable results.

The key factor is also the timing of the measurement. Because the emission of methane to mining excavations depends largely on the scope of mining works performed (see chapter 5), methane concentration measurements should not be taken during the shift changes or when the mine has stopped production, which leads to their decrease.

There is no doubt that temporal emissions data from individual ventilation shafts are a valuable source of information for a verification of top-down approaches. Nonetheless, all the above-described factors can significantly impact the magnitude of the differences when comparing instantaneous emission results with measurement data obtained with instruments onboard aircrafts. With that being said, it is essential that the data for the verification should be reliable and reflect the actual values of emissions from individual point sources as much as possible.

7 Summary and conclusion

Anthropogenic methane emissions pose a serious threat to the Earth' climate. The sources of their emissions are diverse and very scattered. Accurate determination of methane emissions requires an integrated monitoring system primarily based on a combination of top-down and bottom-up approaches. The verification of methane emissions using onboard apparatus on a larger, regional scale is slightly simpler due to the access to annual emission data from various inventories. Accurate determination of emissions on the local scale from coal mines, however, requires instantaneous data, which is very difficult to obtain due to their lack in inventories. As part of this article, we analyzed temporal emission data for 15 ventilation shafts of underground coal mines in the USCB area and determined the factors influencing their variability. This knowledge is essential when it comes to verifying the data achieved during the CoMet 1.0 campaign that took place from May 14 to June 13, 2018. The methane concentrations in examined shafts ranged from 0.00 to 0.55 % and were subject to a significant variation on a day-to-day basis. The main factors that influence the concentration and emission variability are saturation of the particular seams with methane (methane content), the permeability of the rock-mass, the scope of mining works performed in the excavated longwalls (coal output), and the abrupt outflow of methane from fractures and cracks.

The presented temporal data for the CoMet 1.0 observation period (from May 14, 2018, to June 13, 2018) revolved that individual coal mines released between 61.11 to 60.02 kg min^{-1} of methane, which results in 390.92 kt of methane per day for all mines. Conversion of this number for 12 months provided the average emission at a level of 142.68 kt yr^{-1}, which is lower than WUG data by 27% and E-PRTR by 36%, respectively. Additionally, data for individual coal mine facilities were both, over or underestimated. The discrepancies between temporal data and both inventories result from, firstly, following the assumption that the methane concentrations in the ventilation shafts are stable, which is not valid, secondly the methodology of measurements and frequency and the timing of measurements. All the above-described factors can significantly impact the magnitude of the differences when comparing

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instantaneous emission results with measurement data obtained with instruments on board of aircraft. With that being said, it is essential that the data for the verification should be reliable and reflect the actual values of emissions from individual point sources as much as possible. It is recommended to achieve this by using a standardized emission measurement system for all coal mines, preferably the SMP-NT/A methane fire teletransmission monitoring system which most coal mines are equipped with. Although it is aimed at checking the preset legal criteria of methane concentration, it could be easily customized for gas flow quantification, which requires more accurate and precise measurements. Using this system will also exclude the influence of such factors as frequency and timing of measurements on the value of temporal emissions. This would require continuous methane concentration measurements and reporting them on a monthly basis as a weighted average, taking as a weight the time of a given concentration in the ventilation shaft. In addition, separating the emissions form individual ventilation shaft and methane drainage stations would be extremely beneficial to help closing the gap between bottom-up and top-down approaches for coal mine emissions. It is important since the emissions of non-utilized methane from the methane drainage station are not continuous, but intermittent.

With all that being said, any changes to the monitoring and reporting regulations must always be agreed upon between policymakers and mine managers. That will allow them to accurately assess their financial possibilities related to implementing new measurement methods or adaptation of the existing ones.

Data availability. Emission data presented here form one of the core components of the data set "Emissions of CH4 and CO2 over the Upper Silesian Coal Basin (Poland) and its vicinity (4.01)" available at https://doi.org/10.18160/3k6z-4h73.

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