



Direct methane measurements in a coal mine ventilation shaft: instrument intercomparison and emission estimates

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Abstract. Methane released through coal mine ventilation shafts is a major source of anthropogenic greenhouse gas
15 emissions. Reliable quantification of ventilation air methane (VAM) is increasingly important for emission reporting and mitigation, yet long-term in-situ datasets remain scarce. This study presents one year of continuous methane measurements obtained in an exhaust ventilation shaft of an underground hard coal mine in the Upper Silesian Coal Basin (Poland). High-resolution measurements from a tunable diode laser absorption spectroscopy (TDLAS) analyser were compared with data
20 from the mine's routine monitoring system based on catalytic pellistor sensors. Methane concentrations varied between 0.15 and 0.45% CH₄ and exhibited pronounced diurnal, weekly, and seasonal variability primarily associated with mining activity. The pellistor sensor reproduced long-term concentration trends but systematically underestimated methane levels. Following recalibration against the TDLAS measurements, agreement improved substantially ($R^2 = 0.93$), demonstrating that corrected pellistor datasets can support quantitative CH₄ assessments. Methane emission rates were derived from combined
25 concentration and airflow measurements and ranged from 0.8 to 1.7 t CH₄·h⁻¹. Total annual methane emissions from the monitored ventilation shaft were estimated at 10.7 ± 0.93 kt CH₄·yr⁻¹. Emission variability closely followed changes in mining activity and showed stronger relationships with longwall advance than with coal production alone. The resulting methane emission factor was 5.1 ± 1.0 m³ CH₄·t⁻¹ coal, while a geometrical emission factor of 13.4 ± 2.4 m³ CH₄·m⁻² of longwall advance was identified. These results demonstrate the value of continuous high-resolution monitoring for
30 improving methane emission quantification, evaluating routine mine monitoring systems, and supporting measurement-based approaches to mine-level methane reporting.

Keywords: Coal mine methane, Ventilation shaft, Emission factor, TDLAS sensor, Pellistor sensor, Upper Silesian Coal Basin



1 Introduction

35 Methane release from underground coal mining, released through gas drainage systems and ventilation shafts, represent a significant source of anthropogenic emissions and are of major importance for both mine safety and climate-change mitigation. The intensity of methane release is often controlled by a combination of geological conditions, coal seam properties, mining methods, gas drainage practices, and the design and operation of mine ventilation systems (Kędzior and Dreger, 2023; Karacan et al., 2011; Swolkień, 2020). Ventilation systems play a dual role: they provide breathable air to
40 underground workings while simultaneously diluting methane concentrations to prevent the formation of explosive mixtures (Ralston et al., 2015; Krause and Krzemień, 2014).

Ventilation air methane (VAM) typically occurs at relatively low concentrations (0.1–0.8% CH₄); however, the large volumetric airflow rates required for safe mine operation result in globally significant methane emissions to the atmosphere (Su et al., 2008; Swolkień et al., 2022; IEA 2026). In Poland, where coal production is concentrated in the Upper Silesian
45 Coal Basin (USCB), VAM accounts for approximately 60–65% of total methane emissions from underground mines (State Mining Authority, 2025). Despite a long-term decline in coal production, methane emissions have not decreased proportionally, largely due to increasing mining depth and the exploitation of more gas-rich coal seams.

Methane concentrations in ventilation shafts are routinely monitored by automatic gasometry systems installed in underground mines. These systems typically rely on thermocatalytic (pellistor-type) sensors, which are robust and widely
50 used in safety monitoring due to their capability to operate over a wide concentration range. However, their applicability for quantitative emission assessment is limited by relatively high measurement uncertainty, sensitivity drift, and reduced response to rapid concentration changes (Goodman et al., 2008; Nęcki et al., 2026; Swolkień et al., 2022). As a result, methane emission inventories based on in-mine monitoring often carry significant uncertainty.

Recent advances in optical sensing technologies, including tunable diode laser absorption spectroscopy (TDLAS), non-dispersive infrared (NDIR), and Fourier transform infrared (FTIR) spectroscopy, enable high-precision, continuous methane
55 measurements under field conditions. These techniques offer improved sensitivity, selectivity, and temporal resolution compared with conventional sensors, although their performance may be affected by ambient temperature, humidity, and dust loading (Gao et al., 2013; Jiang et al., 2018; Xu and Chen, 2012; Tian et al., 2022; Liang et al., 2015; Tang et al., 2014). Although optical techniques generally provide higher precision and temporal resolution than conventional mine monitoring
60 systems, their implementation in routine ventilation monitoring remains limited. Long-term field evaluations under operational mining conditions are still scarce, and systematic intercomparisons with standard mine sensors are required to support the wider deployment of these technologies.

Methane emissions from coal mining have been quantified using a range of approaches, including in situ measurements, flask sampling, atmospheric inversion, and mass-balance techniques based on ground-based, airborne, and satellite
65 observations (Zazzeri et al., 2015; Menoud et al., 2021; Fiehn et al., 2023; Bezyk et al., 2025; Knapp et al., 2023; Andersen et al., 2023; Nickl et al., 2020; Heltzel et al., 2022; Luther et al., 2019). While these methods provide valuable insights at



regional and basin scales, they often rely on limited temporal coverage or indirect inference of emission rates. As a consequence, there remains a lack of long-term, high-resolution datasets that directly link methane emissions from individual ventilation shafts to mining activity and operational parameters.

70 Previous studies conducted in the Upper Silesian Coal Basin have revealed substantial variability in methane emissions based on ground-based measurements, airborne campaigns, and satellite observations (Gałkowski et al., 2021; Förster et al., 2025; Kostinek et al., 2021). However, these approaches typically provide limited temporal coverage and therefore cannot fully resolve methane emission dynamics at the scale of individual ventilation shafts or directly relate observed variability to specific mining activities. This highlights the need for continuous high-resolution VAM measurements capable of capturing
75 both short-term fluctuations and long-term changes under real operating conditions. Such datasets are essential for improving mine-level emission factor estimates, reducing uncertainties in national GHG inventories, and supporting recent regulatory requirements, including the European Union Regulation (EU) 2024/1787 on methane emissions in the energy sector (Official Journal of the European Union, 2024). In particular, direct, continuous measurements at the ventilation shaft scale offer a unique opportunity to validate top-down emission estimates and to better constrain the temporal variability of methane
80 release under real operating conditions (Rend et al., 2023; Wu et al., 2026).

This study addresses this knowledge gap through a full year of direct, high-resolution methane measurements conducted within an active coal mine ventilation shaft. Continuous CH₄ monitoring using a TDLAS-based Axetris LGD analyser was combined with data from the mine's automatic gasometry system based on catalytic pellistor sensors, enabling a systematic evaluation of sensor performance under real operating conditions. By integrating methane concentration measurements with
85 ventilation airflow records, methane emission rates were quantified across seasonal, weekly, and diurnal timescales and linked to operational parameters, including coal production and longwall advance. Site-specific methane emission factors were subsequently derived and evaluated against reported inventory values.

The main contributions of this study are threefold: (i) the generation of a unique year-long dataset of direct in-shaft methane measurements from an underground coal mine ventilation system, (ii) a systematic intercomparison and recalibration of
90 optical (TDLAS) and catalytic (pellistor) methane sensors under operational mine conditions, and (iii) the quantification of methane emissions and emission factors in relation to mining activity, including coal production and longwall advance. Together, these results provide new insights into methane emission dynamics and support the development of measurement-based approaches for mine-level methane reporting.

2 Study site and mine ventilation system design

95 2.1 Geology and mine layout

The Upper Silesian Coal Basin (USCB), located in southern Poland and the Czech Republic, is one of the largest bituminous coal basins in Europe, covering ~7,500 km². The basin contains a wide range of coal ranks, from non-coking to high-rank coals, and is characterized by increasing coalification with depth and toward the western part of the basin (Sechman et al.,



2013; Kędzior and Dreger, 2022; Krzeszowska, 2024; Jureczka, 2005). The present study was conducted in a hard coal mine located in the Rybnik Mining District (western USCB), characterized by medium methane content corresponding to category III methane hazard ($4.5\text{--}8.0\text{ m}^3\text{ CH}_4\cdot\text{Mg}^{-1}$ coal, DAF) (Szurgacz et al., 2020). The mining concession area covers $\sim 21.8\text{ km}^2$, with estimated recoverable resources of 144.6 Mt. Current exploitation is conducted at depths of $\sim 700\text{ m}$ below ground level (b.g.l.), while shallower levels have already been mined out.

The coal seam thickness ranges from 1.4 to 2.1 m and is overlain by Carboniferous shale, claystone, and sandstone. Coal extraction is carried out using a fully mechanized longwall system. During the study period, the number of active longwall panels decreased from four (July 2024–January 2025), to three (February–May 2025), and two panels (June–July 2025). Average longwall face lengths ranged from 160 to 190 m, with a planned production rate of $\sim 2,000\text{ Mg}\cdot\text{day}^{-1}$ per panel. Mining operations are conducted in four daily shifts I (06:30–14:00), II (12:30–19:30), III (17:30–01:00), and IV (23:00–06:30), which directly influence methane release patterns and ventilation dynamics within the mine.

2.2 Mine ventilation system

The mine ventilation system consists of three intake shafts and two exhaust shafts, including Shaft V (depth 400 m) and Shaft VII (depth 540 m, partially flooded), which ensure continuous airflow through the underground workings (Pierchała and Czuga, 2019). Longwall panels are ventilated using a boundary “U-type” configuration, in which fresh air is supplied via the maingate, flows along the longwall face, and is discharged through the tailgate into return airways (Saki, 2017). On average, $\sim 1,000\text{ m}^3\cdot\text{min}^{-1}$ of fresh air is supplied to each longwall panel through the maingates. The return airflow from active longwall panels is directed toward two exhaust shafts, with the studied shaft (Shaft V) ventilating workings at a depth of $\sim 700\text{ m}$ b.g.l. The shaft is connected to a surface ventilation system including a main horizontal channel ($\sim 28\text{ m}$ long, $4 \times 4\text{ m}$ cross-section), a fan station, and vertical diffusers discharging air to the atmosphere (Fig. 1).

Under typical operating conditions, shaft airflow velocity ranges from 12.1 to $14.8\text{ m}\cdot\text{s}^{-1}$, corresponding to volumetric flow rates of $\sim 11,600$ to $14,200\text{ m}^3\cdot\text{min}^{-1}$. The airflow is highly turbulent, which influences methane mixing and transport processes within the shaft. Air temperature in the ventilation stream varies between 15.6 and 19.8°C . The ventilation system is equipped with an automatic gas monitoring network, including airflow sensors (anemometers) and thermocatalytic methane sensors (pellistors), which provide continuous measurements of gas concentration and flow. These measurements form the basis for operational safety monitoring and are used in this study for comparison with high-resolution optical measurements.

Gas control in the mine includes continuous monitoring of CH_4 , CO_2 , CO , O_2 concentrations, airflow velocity, air pressure, and electrical parameters of fan motors. Methane is measured by applying the pellistor-type sensors, while other gases are detected by electrochemical sensors (Valoski, 2010; Goodman et al., 2008; McPherson, 2009). Continuous gas monitoring in longwall areas and mine workings is based on: (i) airflow velocity measurements using AS-3 anemometers (resolution $0.05\text{ m}\cdot\text{s}^{-1}$; accuracy $\pm 0.1\text{ m}\cdot\text{s}^{-1}$ within the range $0.1\text{--}10\text{ m}\cdot\text{s}^{-1}$), and (ii) real-time methane concentration measurements using



MM-4 thermocatalytic methanometers operating in two detection ranges (0–5% CH₄ with ±0.1% accuracy using a pellistor sensor, and 5–100% CH₄ with ±3% accuracy using a conductivity bridge) (Brodny et al., 2023).

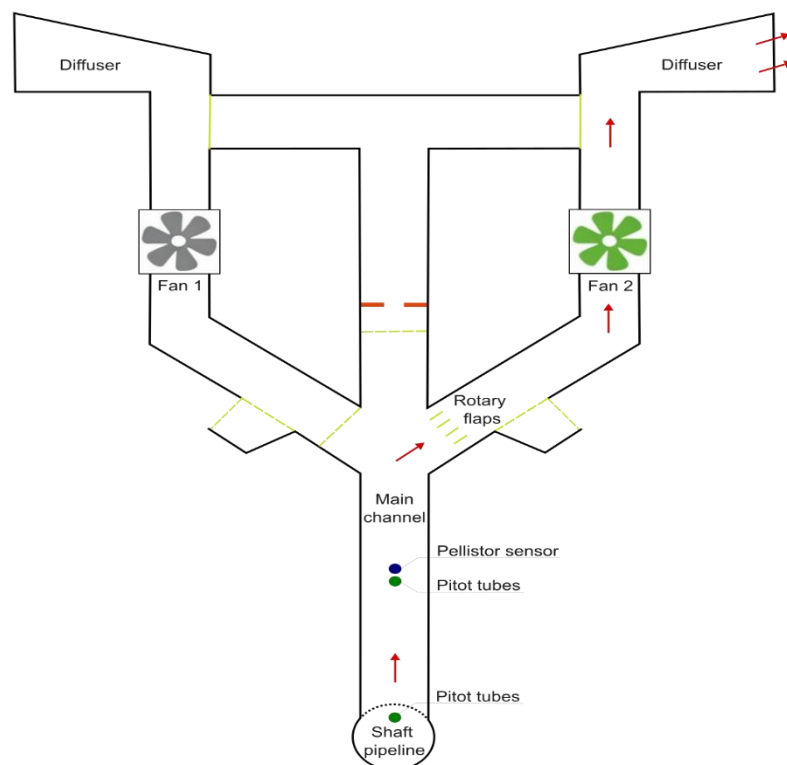


135 **Figure 1: Views of the monitored ventilation shaft, including the main channel and fan station with two diffusers.**

2.3 Operational conditions and airflow variability

Ventilation airflow in the exhaust shaft is controlled by high-capacity surface fans operating under variable load conditions. The main horizontal channel of the examined shaft is connected to the rotary flap control system, which allows switching between fans, and further to the two fan ducts, fan station, and twin vertical diffusers discharging air at 15 m a.g.l. (Fig. 2).

140 Under average operating conditions, the main fan pressure is ~2.99 kPa and the motor power is about 722 kW. The system is subject to periodic operational changes, including alternating fan operation and short maintenance-related interruptions (typically <15 min), which may influence short-term airflow variability.



145 **Figure 2: Scheme of the examined ventilation shaft with the automatic gas monitoring system.**

Airflow measurements are performed using Pitot tube systems installed within the shaft and the main ventilation channel (Fig. 2). A Pitot tube located in the main channel is connected to a manometer that records dynamic pressure in the shaft. The monitoring system records dynamic pressure and airflow parameters continuously, providing input data for ventilation control and methane emission calculations.

150 A new fan station at Shaft V was launched in September 2009 as part of a major restructuring of the mine ventilation network, which comprises over 95 km of workings. During the study period, a significant upgrade of the ventilation monitoring system was implemented (March 2025), including the installation of new Pitot tubes and an increase in data acquisition frequency from 1-minute intervals to 1 Hz. This improvement enhanced the temporal resolution and reliability of airflow measurements used in the subsequent analysis. Short-term variability in airflow results from changes in fan
 155 operation, atmospheric conditions, and ventilation control adjustments, which directly affect methane dilution and influence calculated emission rates.



3 Methods and analytical procedures

3.1 Instrumental setup for methane measurements

Continuous methane monitoring in the exhaust ventilation shaft was conducted over a one-year period using a tunable diode laser absorption spectroscopy (TDLAS) analyser (Axetris LGD). The system was operated under high-humidity and particle-rich conditions typical of ventilation air in underground coal mines. The sampling inlet consisted of a 1/4-inch stainless steel tube installed directly in the main ventilation channel at the same location as the mine's automatic gasometry (pellistor) sensor, enabling direct comparison of both measurement systems (Fig. 2).

The sample gas was extracted continuously and transported to the measurement unit installed within the shaft infrastructure (rotary flaps room). To reduce the influence of high moisture content, the sampled air was passed through a custom-designed drying module consisting of a heated inlet (65°C) and a two-stage condensate separation system (Fig. 3). Condensed water was periodically removed using an automated purging system (solenoid valves controlled by a programmable digital timer) to ensure stable and uninterrupted gas flow during long-term operation. Particulate filters were installed upstream of the analyser to prevent contamination of optical components.

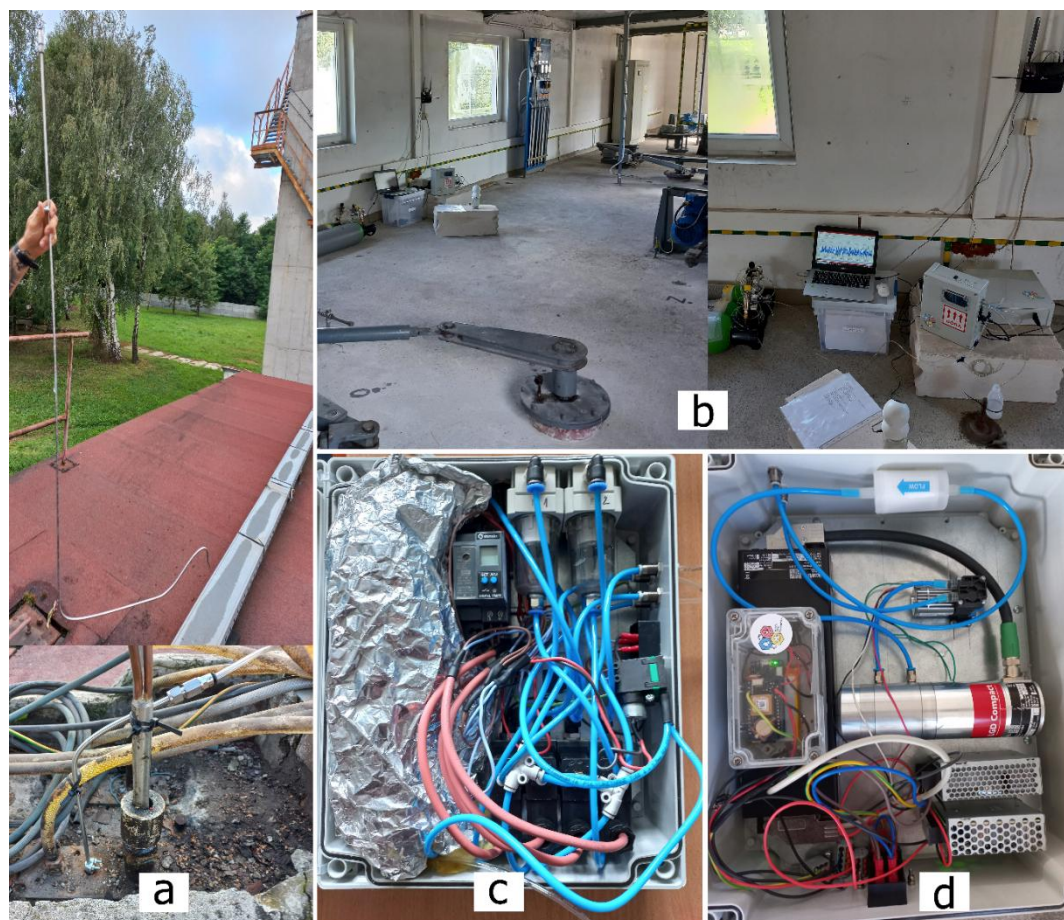


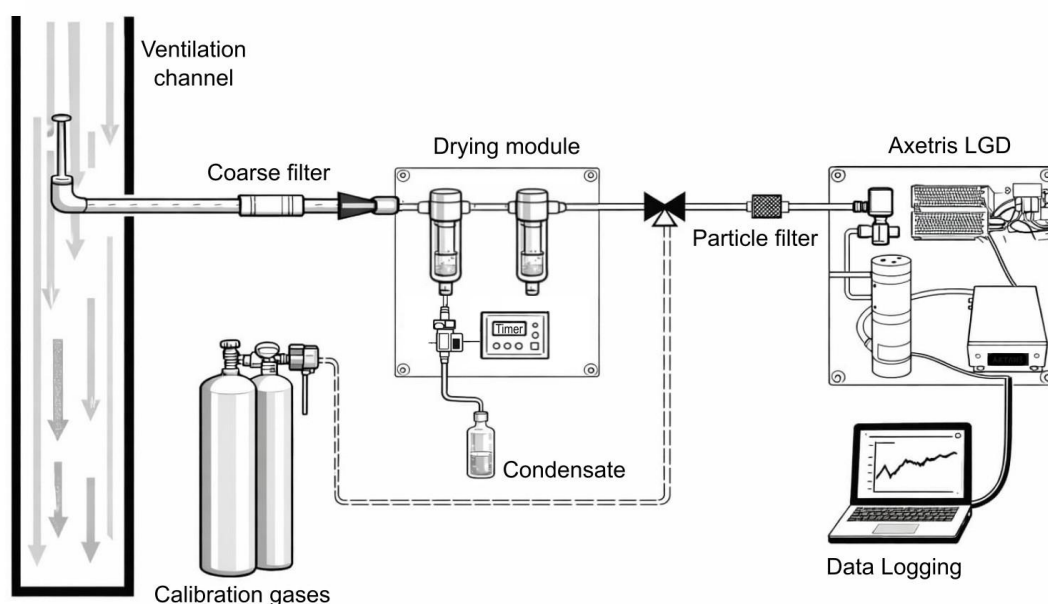
Figure 3: Experimental set-up for continuous CH₄ monitoring in the mine ventilation shaft, including (a) sampling inlet; (b) view of the rotary flaps room of the shaft showing system installation; (c) water vapour removal/drying module; (d) Axetris LGD analyser.

- 175 Methane concentration was measured using an Axetris Compact-A CH₄ analyser based on near-infrared TDLAS technology ($\lambda \approx 1.65 \mu\text{m}$) with a multipass optical cell. Patented modulation-based noise suppression technology ensures consistent high performance over an extended operational period. The device supports a wide measurement range, including a low range of 0–100 ppm for trace gas detection (precision: 0.8 ppm or 0.6% of reading) and a high range up to 40,000 ppm (precision: <250 ppm). The instrument provides fast response ($\leq 1.8 \text{ s}$) at $2 \text{ L}\cdot\text{min}^{-1}$ flow rate and high selectivity (Axetris, 2025).
- 180 Measurement data were recorded continuously using a dedicated acquisition system, allowing real-time monitoring and long-term data storage.

The Axetris analyzer was housed in a protective enclosure suitable for field deployment, with a micro diaphragm pump providing adjustable sample flow and a continuous electrical power supply. Particulate filtration upstream of the analyzer inlet prevented contamination of optical components, contributing to long-term measurement reliability. The system was



185 equipped with a Wi-Fi router, enabling remote access for real-time monitoring and system control, minimizing maintenance efforts. A schematic overview of the sampling and measurement system is shown in Fig. 4.



190 **Figure 4: Schematic diagram of the main components of methane measuring system. Air was sampled from the shaft channel via the inlet, passes through a coarse particle filter, then through the drying module, and finally through fine particle filter delivered to the Axetris LGD analyser.**

3.2 Calibration and validation of measurements

Calibration of the TDLAS analyser was performed using certified methane reference gas mixtures at three concentration levels (1023, 2839, and 4834 ppm CH₄), covering the range typically observed in ventilation air. Each calibration was
 195 conducted under stable flow conditions, and the analyser response was recorded over fixed time intervals after signal stabilization. The calibration procedure ensured high linearity of the instrument response across the working range ($R^2 \approx 0.999$) and demonstrated stable performance under field conditions. The relative expanded uncertainty of the analyser remained below 1.4% of the measured value (see Supplement, Fig. S1).

Independent validation of the measurement system was conducted using gas samples collected in PTFE bags and analysed in
 200 the laboratory using a cavity ring-down spectroscopy (CRDS) analyzer (Picarro G2201-i). The comparison showed strong agreement between both measurement techniques, confirming the accuracy and robustness of the TDLAS measurements (see Supplement, Fig. S2).



3.3 Data processing and statistical analysis

Methane concentration data were recorded at high frequency and subsequently aggregated to 1-minute and 1-hour averages for further analysis. Descriptive statistics, including mean values, standard deviations, and percentile distributions, were used to quantify temporal variability across diurnal, weekly, and seasonal timescales. Tukey's range test, a single-step multiple comparison procedure with a significance level of $p = 0.05$, was applied to compare summarized CH_4 concentration ranges across different time periods during the monitoring.

Methane concentrations recorded by the mine's pellistor sensor were synchronized with the TDLAS dataset using 1-minute averaging. To ensure consistency between measurement systems, a linear scaling approach including both offset and proportional correction was applied to recalibrate pellistor data against the TDLAS reference dataset (see Supplement, Text S2). The agreement between datasets was evaluated using regression analysis and residual diagnostics. The relationship between methane concentration and ventilation airflow was analysed using Orthogonal Distance Regression (ODR), which accounts for uncertainties in both variables. Prior to regression analysis, outliers were removed using a Mahalanobis distance-based filter (Poch and Villaescusa, 2012).

Ventilation air velocity and volumetric flow rates, obtained from the mine's airflow monitoring system installed in the shaft were synchronized with CH_4 concentration data. To assess temporal variability in methane–airflow relationships, a moving-window analysis was applied using a 13-day sliding window (± 6 days). For each time step, correlation coefficients and regression slopes were calculated, allowing the identification of periods dominated by ventilation-driven dilution or increased methane release.

3.4 Estimation of methane emission rates

Methane emission rates from the ventilation shaft were calculated by combining measured CH_4 concentrations with corresponding ventilation airflow rates obtained from the mine's monitoring system. Emission flux (Q) was calculated as:

$$Q = C \cdot F_{\text{air}} \cdot \rho \quad (1)$$

where C is methane concentration (expressed as a volume fraction), F_{air} is the volumetric airflow rate ($\text{m}^3 \cdot \text{min}^{-1}$), and ρ is methane density ($0.665 \text{ kg} \cdot \text{m}^{-3}$ under standard conditions).

Airflow rates were derived from measured air velocity and the cross-sectional area of the ventilation channel. Methane emission rates were calculated at high temporal resolution (1 minute) and subsequently integrated to derive hourly, monthly, and annual emissions. To investigate the influence of mining activity, emission rates were analysed in relation to operational parameters, including coal production and longwall advance (see Supplement, Text S3). Statistical relationships were quantified using regression analysis at multiple temporal scales.

Finally, emission factors for the coal mine were derived by normalizing total methane emissions by the net coal production volumes obtained from mine operational records, with related uncertainties from both emission and production datasets (EMEP, 2023; Kholod et al., 2020).



235 3.5 Uncertainty analysis

Uncertainty of the short-term methane emission estimates was quantified by propagating uncertainties associated with methane concentration, ventilation airflow rate, and methane density:

$$\frac{u(Q)}{Q} = \sqrt{\left(\frac{u(C)}{C}\right)^2 + \left(\frac{u(F)}{F}\right)^2 + \left(\frac{u(\rho)}{\rho}\right)^2} \quad (2)$$

The instrumental uncertainty of the TDLAS analyzer was ~1.4% of the measurements. For typical methane concentrations in the ventilation shaft (0.15–0.45%; 1500–4500 ppm), this corresponds to an absolute uncertainty of approximately ±20–60 ppm CH₄. Uncertainty in airflow measurements represented the dominant contribution to the overall uncertainty. For typical ventilation conditions (11,600–14,200 m³·min⁻¹), the relative uncertainty reached up to ~8%, corresponding to an absolute uncertainty of ±900–1100 m³·min⁻¹. This reflects the combined effects of turbulence, non-uniform flow distribution, and sensor limitations. Uncertainty in methane density, associated with variations in temperature and pressure, remained below 1% and contributed only marginally to the total uncertainty budget. For representative operating conditions (CH₄ ≈ 0.30% and airflow ≈ 12,500 m³·min⁻¹), the methane emission rate is ~25 kg CH₄·min⁻¹. Under these conditions, the combined relative uncertainty of the emission estimate is approximately 8–9%, corresponding to an absolute uncertainty of ±2–2.3 kg CH₄·min⁻¹.

At longer aggregation times, random uncertainty is reduced, while systematic uncertainty associated with airflow measurements remains dominant. For typical hourly emissions of 1.0 – 1.5 t CH₄·h⁻¹, the corresponding absolute uncertainty is approximately ±0.1 t CH₄·h⁻¹, increasing to ±80–120 t CH₄·month⁻¹ for monthly totals (see Supplement, Text S4). The expanded uncertainty of methane emission estimates at a 95% confidence level (*k* = 1.96) remained at approximately 8–9% for the full annual dataset (Morrison, 2020).

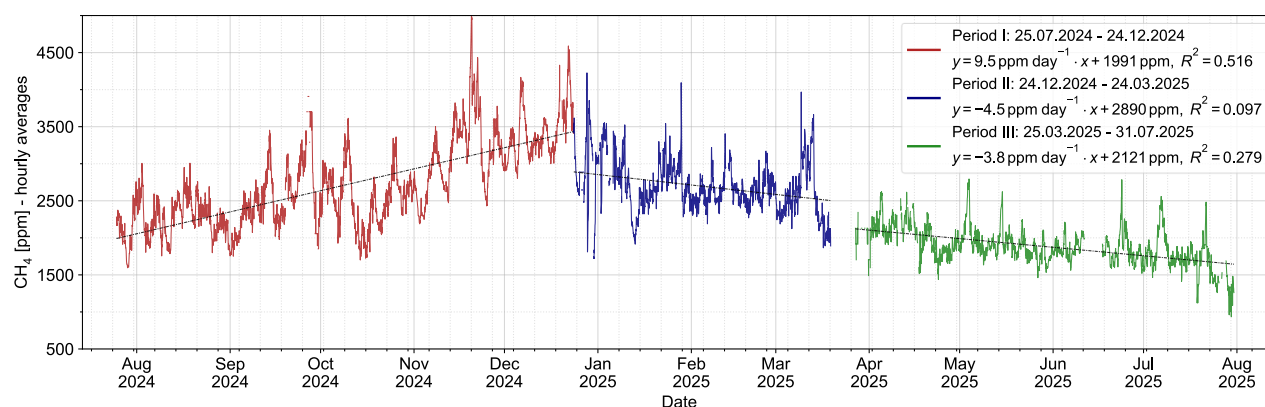
4 Results

255 4.1 Temporal variability of methane concentration in the mine ventilation system

The methane monitoring campaign covered the period from August 2024 to July 2025 and revealed that the ventilation shaft acted as a continuous but temporally variable methane source. Methane concentrations ranged from approximately 1500 to 4500 ppm (0.15–0.45%) and exhibited pronounced seasonal changes (Fig. 5). Three characteristic periods were identified. Period I (August–December 2024) was characterized by relatively stable methane concentrations and a gradual upward trend in methane levels at the shaft. Period II (January–April 2025) showed frequent anomalies, represented by episodic peaks, and a disruption to the previous increasing trend. Period III (April–August 2025) is represented by decreased diurnal and medium-term variability, with generally lower and more stable CH₄ concentrations. Overall, the annual trend indicates a decrease in average methane concentration from ~3500 ppm to 1500 ppm over the monitoring period. Statistical analysis further showed that CH₄ concentration data were close to normally distributed, although Q–Q plots revealed deviations from



265 normality in the upper quantiles, particularly during Period I, highlighting the occurrence of high-concentration (“peak”) events (see Supplement, Fig. S3–S5).



270 **Figure 5: Seasonal evolution of hourly averaged methane concentrations in the ventilation shaft during the monitoring period (August 2024 to July 2025). Three characteristic periods (I–III) are identified based on changes in methane concentration variability and mining activity.**

Short-term variability was analysed using weekly aggregation (Fig. 6). Period I showed the highest relative variability (coefficient of variation, CV = 21.39%), although the weekly distributions showed a gradual increase in median CH₄ concentrations without persistent short-term fluctuations. Period II is characterized by substantially lower relative variability (CV = 13.27%), despite broader distributions and the occurrence of several extreme values, reflecting episodic changes in CH₄ release associated with mining activity. Period III had a similar level of relative variability (CV = 13.49%) and a reduced overall concentration range compared with Periods I and II. This behaviour likely reflects the reduced number of active longwall panels during the final phase of the monitoring campaign, resulting in lower overall methane release and a more stable concentration signal at the shaft.

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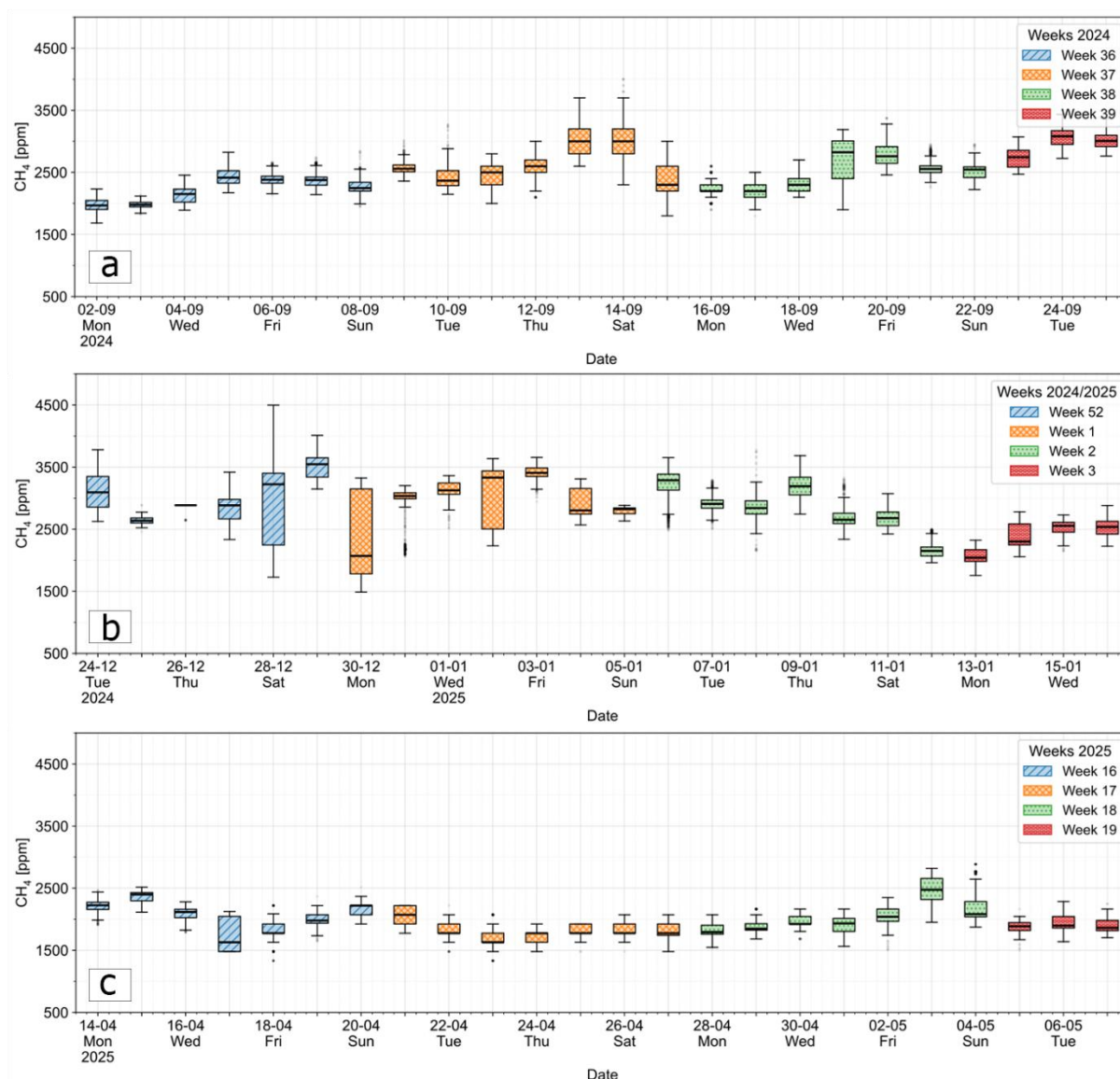


Figure 6: Weekly distribution of methane concentrations in the ventilation shaft for three measurement periods: (a) Period I, (b) Period II, and (c) Period III. Boxplots represent median values, interquartile ranges, and extreme observations for individual weeks.

285 Analysis of diurnal and day-to-day variability shows a clear association with the mining operation schedule (Fig. 7). Methane concentrations generally increase during working days and decrease during weekends. Maxima occur during active production hours, typically between mid-day and early evening. The onset of concentration increase follows the start of the first mining shift (06:30) with an observed delay of ~1.5 hours, and is associated with gas transport time within the ventilation network. Episodic peaks, especially on Sunday mornings, may reflect delayed CH_4 release or residual emissions

290 within the mine.

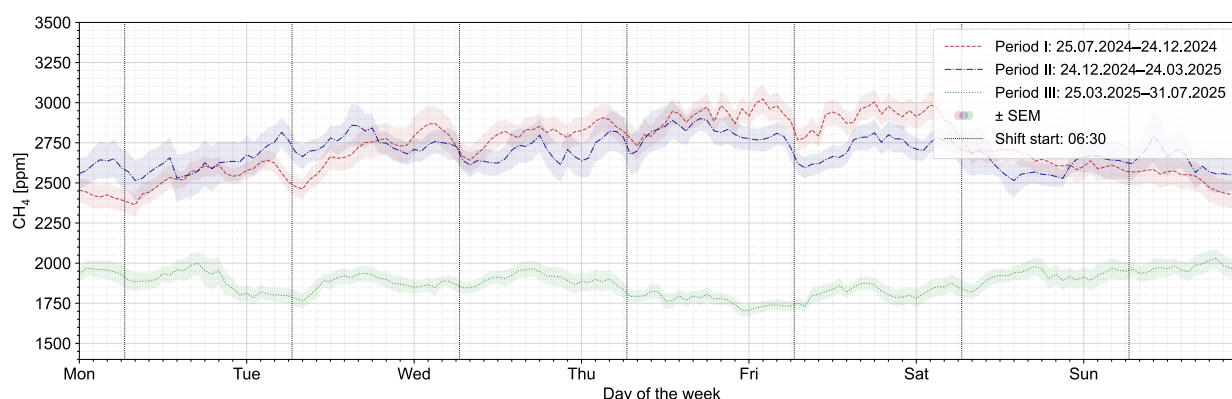


Figure 7: Average diurnal methane concentration profiles in the ventilation shaft for three measurement periods (I–III). Vertical dashed lines indicate the start of the first mining shift (06:30) in the operation schedule.

295 Hourly trends further confirm consistent daily cycles (Fig. 8). Concentration peaks are typically observed during the second and third shifts, while lower values occur during night-time and periods of reduced mining activity (e.g., weekends or non-production hours). Period III, the amplitude of diurnal variability is reduced compared with Periods I and II, indicating a more stable methane emission signal at the shaft, likely associated with reduced variability in gas release from a fewer number of active longwalls and more uniform ventilation conditions. Overall, CH₄ concentration dynamics demonstrate a

300 consistent operational influence, with increases following shift initiation and gradual decreases during non-operational hours.

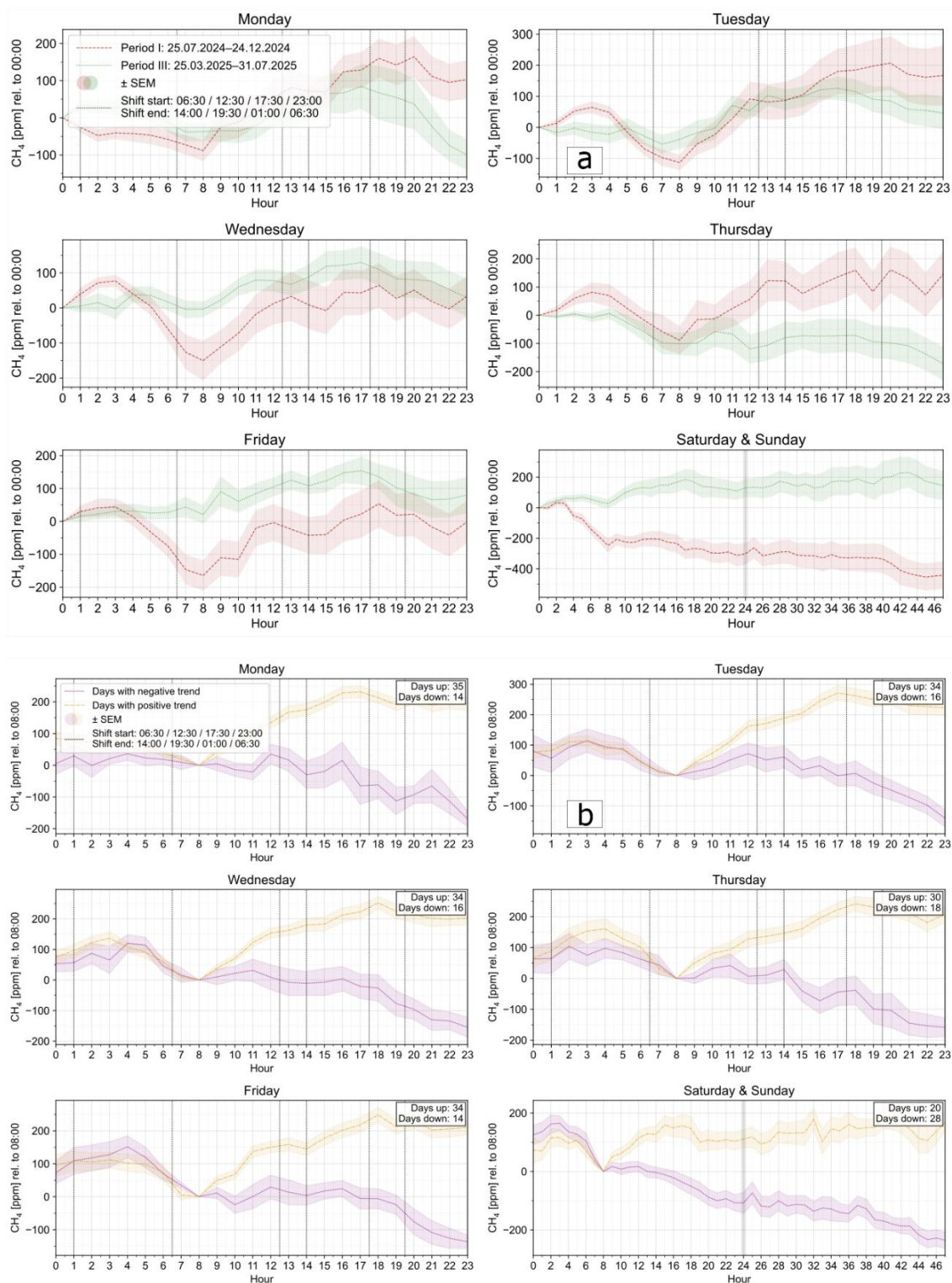




Figure 8: Average hourly methane concentration patterns in the ventilation shaft: (a) diurnal CH₄ concentration profiles grouped by day of the week and measurement period (Periods I and III), referenced to 00:00; (b) average hourly CH₄ concentration profiles separated into days with increasing and decreasing trends, referenced to 08:00 to account for the observed delay (~1.5 h) between the start of mining operations and the corresponding increase in methane concentration in the shaft. Period II was excluded due to high temporal heterogeneity and unstable operating conditions (ventilation-related upgrades in the shaft). Vertical dashed lines indicate the start of mining shifts (I: 06:30–14:00; II: 12:30–19:30; III: 17:30–01:00; IV: 23:00–06:30). Weekend days (Saturday and Sunday) are grouped.

4.2 Relationship between methane concentrations and mine ventilation rates

Differences in CH₄ levels and the efficiency of methane removal by the ventilation system between the identified periods reflect changes in both gas release intensity within the mine workings and the operating conditions of the ventilation network supplying air to the shaft. At the shaft scale, the observed gas concentrations result from: (i) methane inflows from underground sources associated with active longwall panels and surrounding strata, and (ii) dilution rates of this gas by the volumetric airflow rate in the return air stream. As a result, temporal changes in methane concentration cannot be attributed solely to variations in ventilation intensity, but also to changes in gas generation and release within the mine.

A general inverse relationship between CH₄ concentration and ventilation airflow rate is observed (Fig. 9), confirming the role of ventilation as a methane dilution mechanism. However, the strength of this relationship varied considerably between study periods, indicating that changes in methane release intensity also contributed substantially to the observed concentration variability. However, this relationship is not constant over time, reflecting variability in methane source strength. Periods characterized by a stronger negative correlation ($R^2 > 0.2$) correspond to conditions where airflow variations dominate short-term concentration changes, whereas weaker correlations ($R^2 < 0.2$) indicate a stronger influence of variable methane inflow from active production zones. Short-term methane concentration peaks are only partly explained by airflow variability.

In several cases, elevated CH₄ levels occur without a corresponding reduction in airflow, indicating transient increases in methane release intensity (see Supplement, Fig. S6). Such events are consistent with operational processes typical for longwall mining, including localized roof deformation, stress redistribution in the rock mass, or variations in gas drainage efficiency. Conversely, periods of relatively constant methane concentration combined with stable airflow conditions indicate quasi-steady transport conditions, where methane supply from underground sources and dilution by ventilation remain approximately balanced over time. Overall, the methane–airflow relationship demonstrates that ventilation primarily controls methane dilution, whereas temporal changes in methane release from underground workings explain much of the remaining variability. Consequently, methane concentration dynamics cannot be interpreted from airflow changes alone. Therefore, accurate interpretation of methane concentration dynamics in ventilation shafts requires simultaneous consideration of both airflow variability and source-related emission processes.

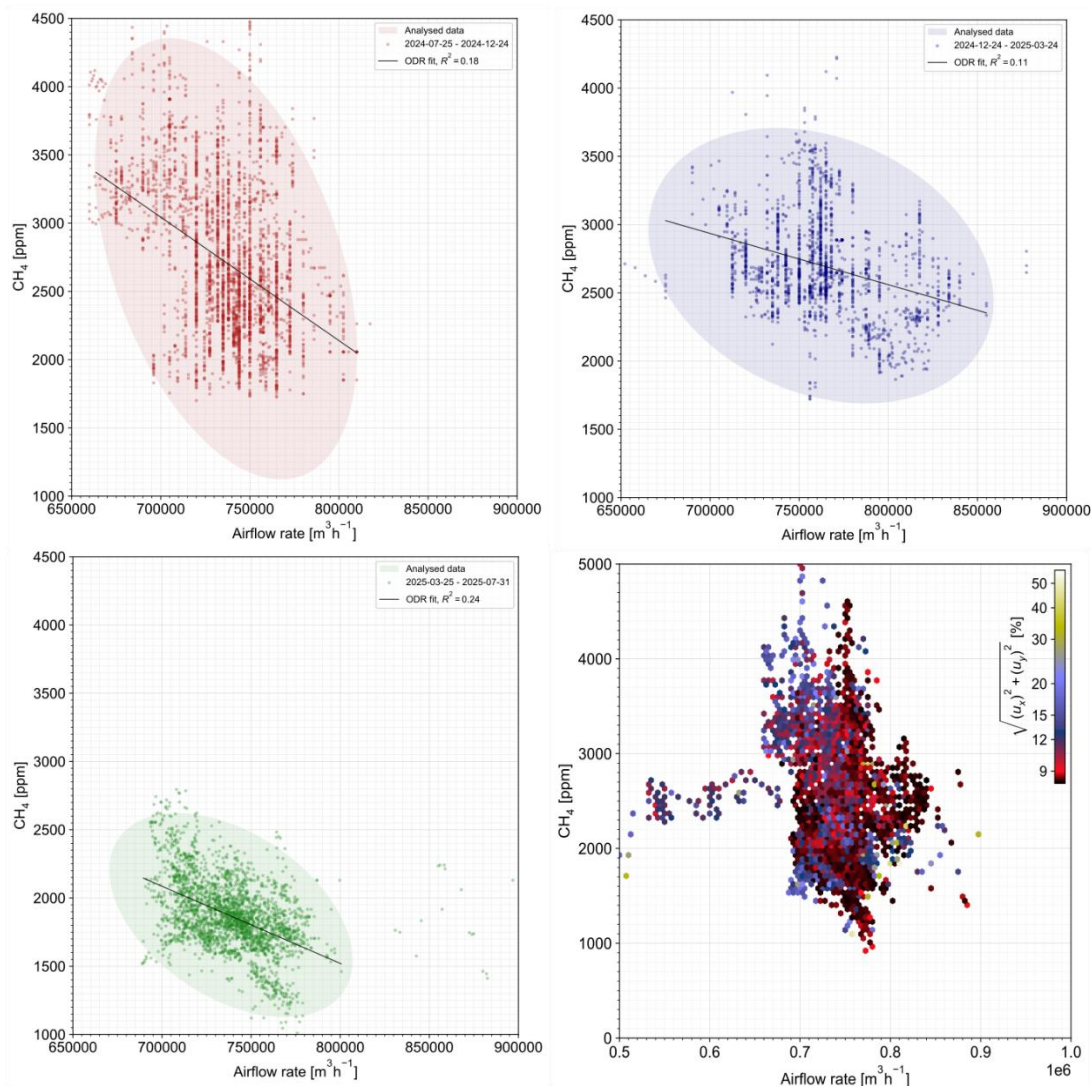


Figure 9: Relationship between hourly averaged methane concentration and ventilation airflow rate in the exhaust shaft. Data are shown separately for three measurement periods (I–III). Solid lines represent Orthogonal Distance Regression (ODR) fits accounting for uncertainties in both variables. The combined dataset (lower right panel) is color-coded by airflow variability.

340 To further quantify the methane–airflow relationship and its temporal variability, hourly data were analysed using a 13-day centered moving window (± 6 days), allowing for robust estimation of short-term correlations under changing operational conditions (Fig. 10). For each time step, correlation coefficients and regression slopes were calculated between CH_4 concentration and ventilation airflow rate. The moving-window approach reduces the influence of short-term fluctuations and provides statistically representative relationships based on sufficient observational samples within each window. The

345 moving-window analysis showed statistically significant negative methane-airflow correlations ($p < 0.01$) for $\sim 70\%$ of the observation period, confirming the importance of ventilation-driven dilution. Strong negative correlations ($r < -0.5$) occurred



during ~30% of the dataset and represent periods in which airflow variability exerted the strongest influence on methane concentration.

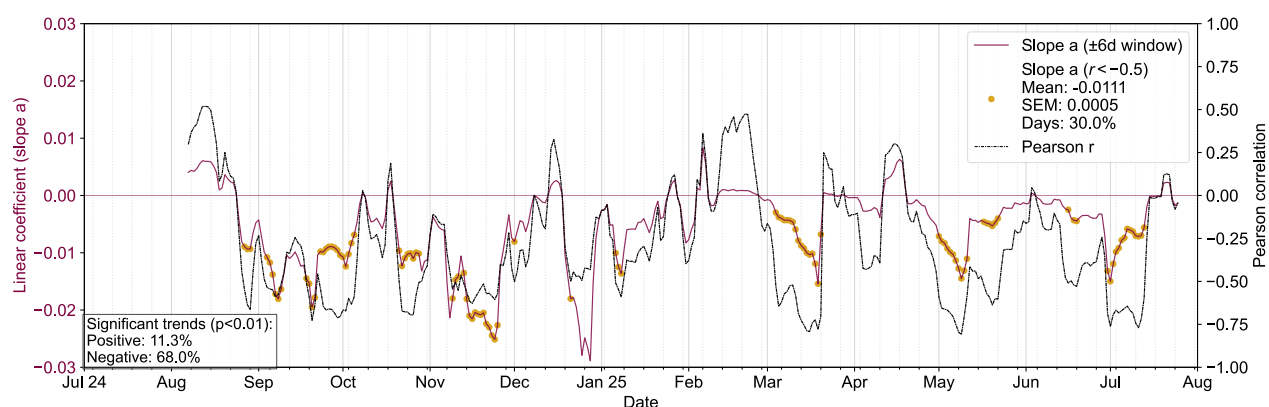
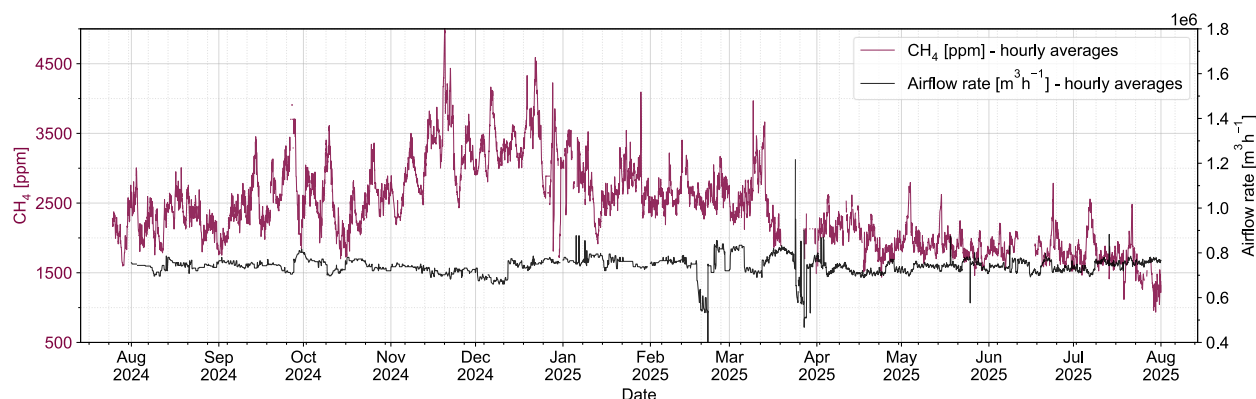


Figure 10: Time series of Pearson correlation coefficients between CH₄ concentration and ventilation airflow rate in the shaft, with corresponding regression slopes expressing methane concentration changes per airflow changes. Orange markers denote periods with strong negative correlation ($r < -0.5$) identified in the 13-day centered moving window.

In contrast, ~12% of observations exhibited positive methane-airflow correlations, indicating that increases in methane release from underground sources outweighed the expected dilution effect. These intervals provide direct evidence that variability in methane inflow can occasionally dominate the concentration signal measured at the ventilation shaft. Such behaviour suggests that airflow variability alone is insufficient to explain concentration changes and that temporal variability in methane release intensity must be considered.

The temporal evolution of correlation coefficients and regression slopes (Fig. 10) demonstrates that the methane–airflow relationship is not stationary and varies throughout the monitoring campaign. Periods with strong negative slopes correspond to ventilation-dominated regimes, whereas periods with weak or positive slopes indicate stronger influence of in-mine CH₄ source variability. Additional analyses performed at different temporal resolutions confirm that methane concentration dynamics in the ventilation shaft are largely controlled by a combination of these two operational factors. Results from the moving-window analysis are consistent with the variability observed in hourly concentration time series and diurnal cycles (see Supplement, Fig. S6), indicating that short-term methane fluctuations are linked to both mining activity and transient changes in ventilation conditions.

For a representative airflow rate of approximately 12,500 m³·min⁻¹, regression slopes indicate that a 1% increase in ventilation flow typically corresponds to a decrease of approximately 100 ppm CH₄ concentration. The elevated airflows recorded during the annual timescale often corresponded to temporary decreases in CH₄ concentration, suggesting that short-term operational adjustment of the ventilation system may influence methane dilution. This relationship quantifies the sensitivity of the ventilation system as a dilution mechanism, although its exact applicability varies depending on the prevailing balance between gas inflow and airflow conditions.



375 **Figure 11: Temporal variation of hourly averaged CH₄ concentration and ventilation airflow rate in the ventilation shaft during the annual measurement period (August 2024–July 2025).**

Monthly regression analyses (see Supplement, Fig. S7) further demonstrate that the relative importance of airflow and methane emission source varies over longer timescales. Months characterized by strong negative slopes (e.g., November 2024, March 2025, July 2025) correspond to conditions where ventilation-driven dilution dominates. In contrast, months with weaker relationships indicate that variability in CH₄ inflow from underground sources is the primary driver of observed concentration changes.

Overall, while ventilation airflow exerts a primary control on methane concentration through dilution, the dominant source of variability lays in the temporal changes of methane release from the mined coal seam. Robust interpretation of methane concentration time series requires simultaneous consideration of both airflow dynamics and source-related processes across multiple temporal scales.

4.3 Evaluation of Axetris and Pellistor sensors

Both the Axetris LGD analyser and the mine-installed pellistor sensor reproduced the principal temporal patterns of methane variability in the ventilation shaft, including diurnal cycles and seasonal trends. However, the pellistor sensor systematically reported lower methane concentrations across the entire measurement range, indicating a persistent calibration bias. This underestimation became more apparent during periods of elevated methane concentration and increased temporal variability, while agreement between the two systems improved during more stable operational conditions. Short-term methane peaks were generally detected by both instruments, although their magnitude was frequently underestimated by the pellistor sensor due to its lower dynamic response and coarse measurement resolution (see Supplement, Fig. S8–S9).

The systematic nature of this discrepancy was confirmed through regression analysis of synchronised one-minute observations. Raw pellistor measurements showed poor agreement with the Axetris dataset ($R^2 = 0.18$) and underestimated methane concentrations by ~30% on average (Fig.12a). After applying calibration corrections based on offset and proportional scaling, agreement improved substantially ($R^2 = 0.93$), while the mean difference between both datasets was



reduced to 0.4% and the relative RMSE decreased to ~7%. These results, presented on figure 12, demonstrate that most of the disagreement between the two systems originated from systematic measurement bias rather than random measurement noise.

Residual deviations remained visible at both low and high methane concentrations and were primarily associated with sensor resolution limitations, response-time differences, and non-linearities in pellistor performance. Nevertheless, the corrected pellistor dataset reproduced methane variability with sufficient accuracy for emission assessment purposes. Consequently, existing mine monitoring networks can produce valuable quantitative information, provided that regular calibration and bias correction procedures are implemented.

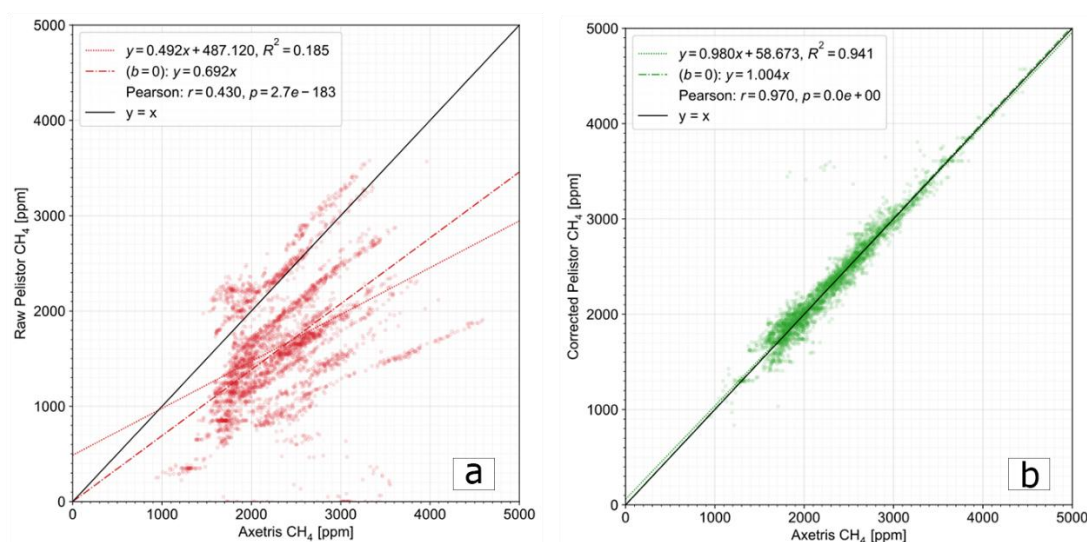


Figure 12: Linear regression comparison of time-synchronized CH₄ concentrations measured by the Axetris LGD analyzer and the pellistor sensor in the ventilation shaft: (a) raw pellistor data and (b) corrected pellistor data after calibration using Axetris as a reference instrument. The recalibration significantly improves agreement between the datasets, as reflected by the increase in the coefficient of determination (R^2) and reduction of systematic bias.

4.4 Estimation of methane emissions from the coal mine ventilation shaft

Methane emission rates from the ventilation shaft were calculated by combining time-resolved CH₄ concentration measurements with corresponding ventilation airflow data. The resulting dataset provides a continuous record of methane release under variable operational and ventilation conditions. At short timescales, methane concentration exhibited substantially greater variability than airflow rate, indicating that fluctuations in emission intensity were primarily controlled by changes in CH₄ release rather than ventilation dynamics (Fig. 11). Periods of elevated CH₄ concentration were frequently associated with slight reductions in airflow, however, several high-concentration events occurred without corresponding airflow changes, suggesting variability in source strength.



Under average operating conditions, with a ventilation airflow rate of $12,500 \pm 400 \text{ m}^3 \cdot \text{min}^{-1}$ and a mean methane concentration of $0.29 \pm 0.11\%$, the estimated methane emission rate was $25 \pm 10 \text{ kg CH}_4 \cdot \text{min}^{-1}$. At hourly resolution, methane emissions ranged from approximately 0.8 to $1.7 \text{ t CH}_4 \cdot \text{h}^{-1}$, consistent with observed variability in both methane concentration and ventilation airflow. Diurnal variability within individual months was moderate compared with longer-term changes, although distinct intra-day emission maxima were observed in selected periods, particularly during afternoon hours (Fig. 13). During pre-winter period of intensified mining activity (November–January), hourly emissions remained consistently high throughout the day, showing relatively stable CH_4 release conditions.

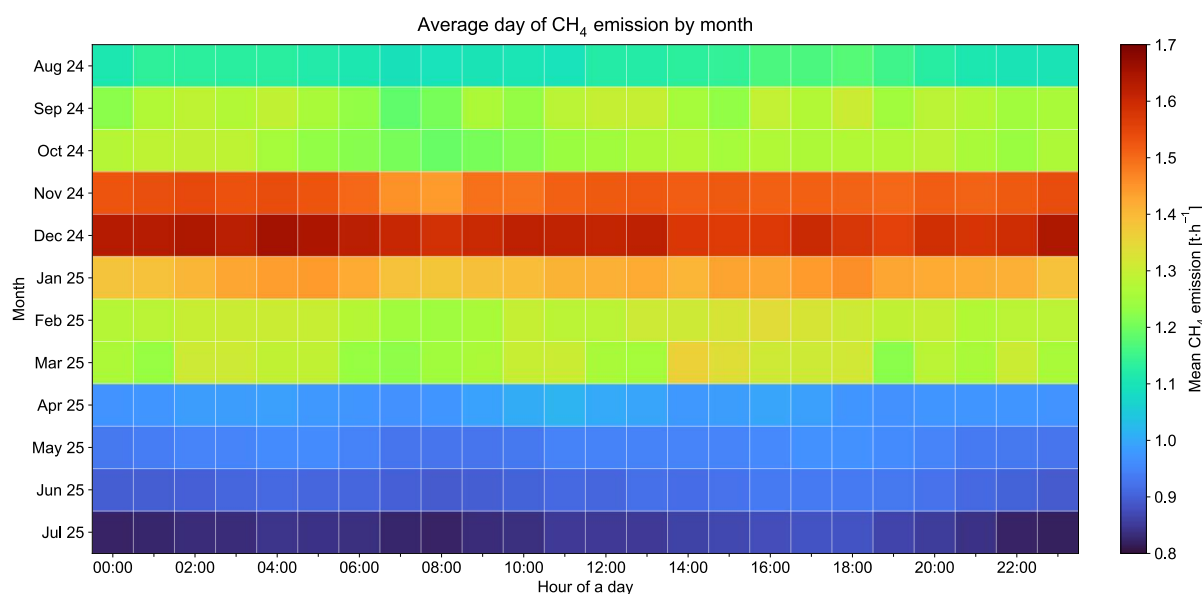


Figure 13: Heatmap of average hourly methane emission rates ($\text{t CH}_4 \cdot \text{h}^{-1}$) by month for the exhaust ventilation shaft during the annual monitoring period (August 2024–July 2025). Warmer colors indicate higher emission rates, highlighting diurnal and seasonal variability in methane release.

A clear seasonal pattern of methane emissions was identified over the annual monitoring period (Fig. 14a). Three characteristic emission periods were distinguished. Period I (August–December 2024): highest emissions, averaging $1060 \pm 140 \text{ t CH}_4 \cdot \text{month}^{-1}$; Period II (January–March 2025): slightly lower emissions, $1034 \pm 80 \text{ t CH}_4 \cdot \text{month}^{-1}$; Period III (April–June 2025): lowest emissions, $720 \pm 40 \text{ t CH}_4 \cdot \text{month}^{-1}$. The observed decrease in methane emissions after March 2025 coincided with a reduction in mining activity, including a decrease in the number of active longwall panels. The transition from four to two active longwall panels coincided with a decrease in mean methane concentration from approximately 3500 ppm to 1500 ppm. When normalized to the number of active longwalls, methane emissions remained relatively stable across periods, averaging approximately: $265 \pm 35 \text{ t CH}_4 \cdot \text{month}^{-1}$ per longwall (Period I); $311 \pm 24 \text{ t CH}_4 \cdot \text{month}^{-1}$ per longwall (Period II); $270 \pm 15 \text{ t CH}_4 \cdot \text{month}^{-1}$ per longwall (Period III).

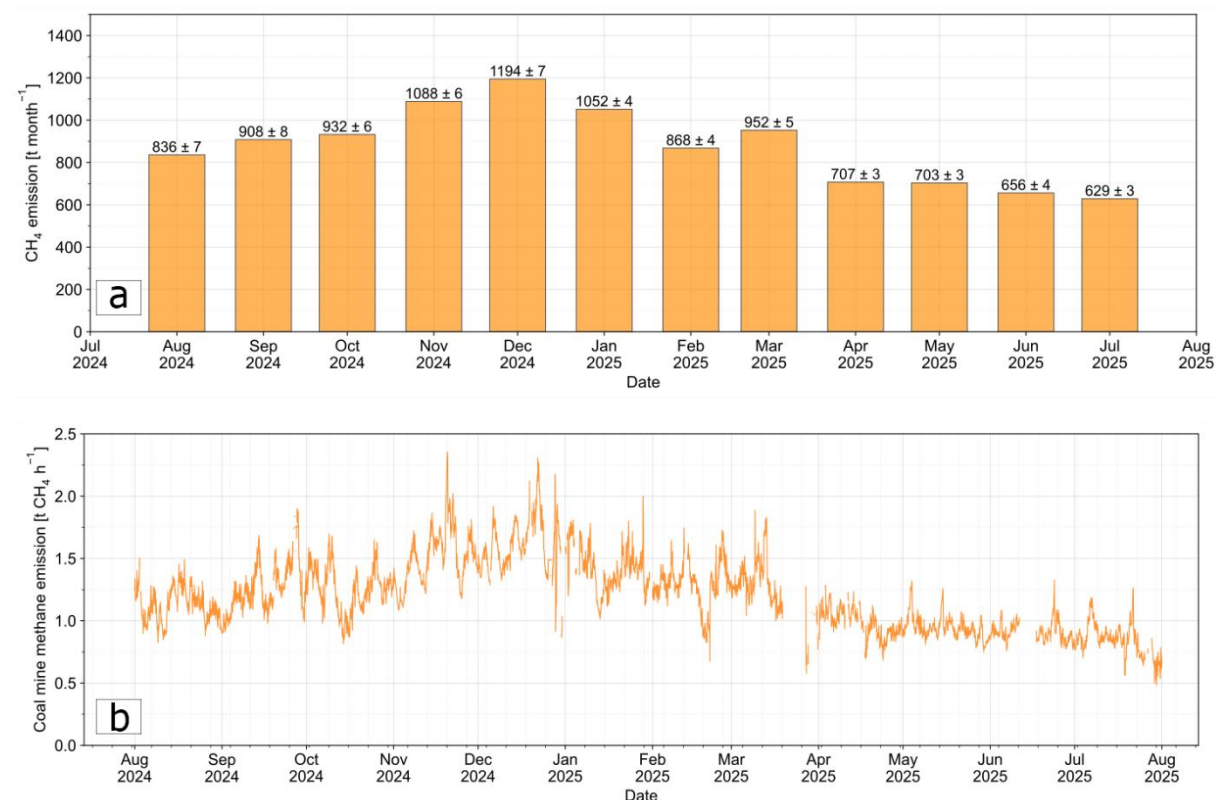
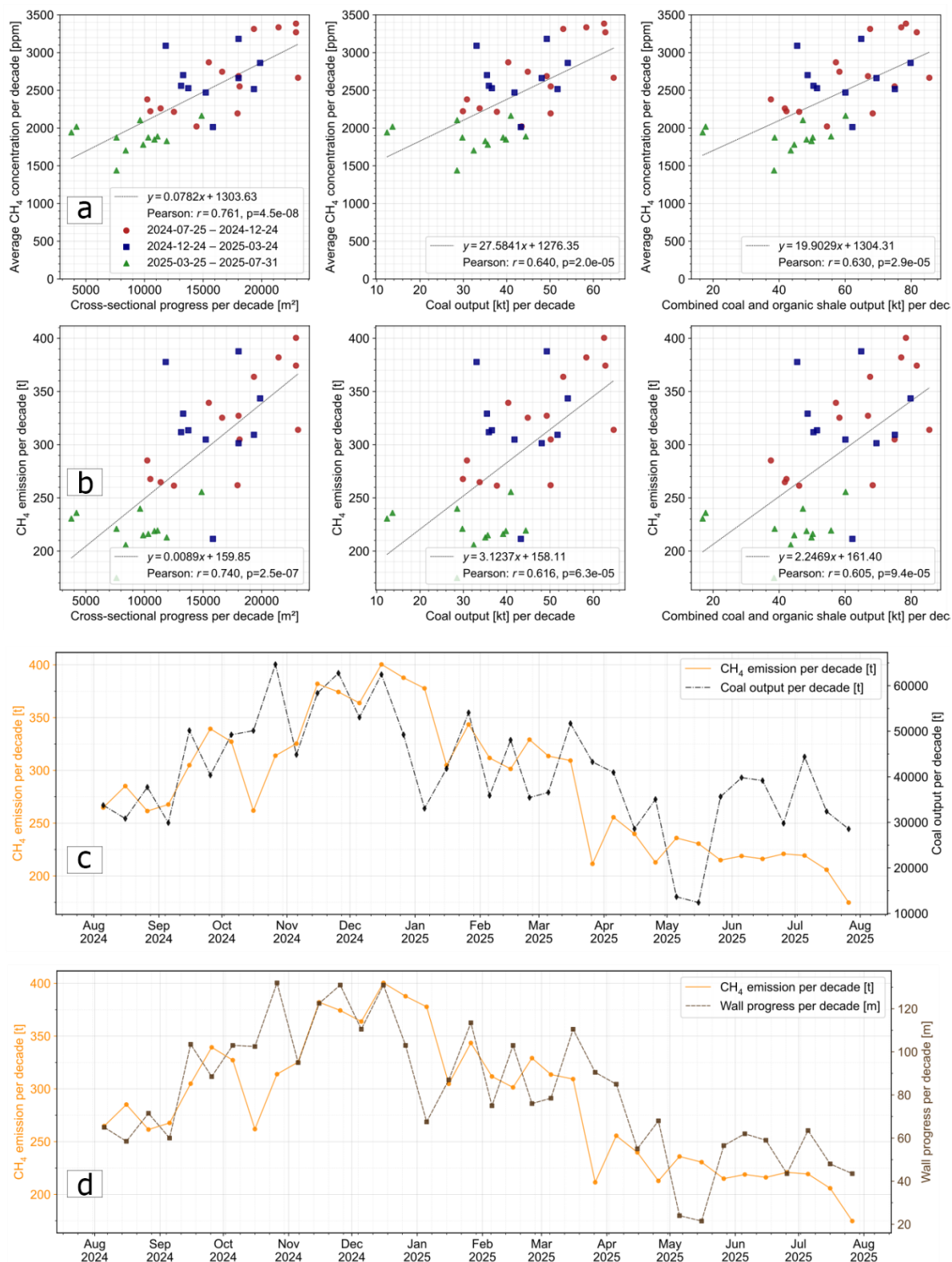


Figure 14: Short- and long-term variability of methane emissions from the ventilation shaft during the monitoring period (August 2024–July 2025): (a) monthly total emissions ($\text{t CH}_4 \cdot \text{month}^{-1}$) and (b) hourly emission rates ($\text{t CH}_4 \cdot \text{h}^{-1}$).

Overall, methane emission rates show clear temporal variability across multiple timescales, with seasonal changes dominating over short-term (e.g., diurnal) fluctuations (Fig. 14b). The highest emission levels were observed during periods of intensified mining activity (Period I), while the reduction in the number of active longwalls resulted in a significant decline in emissions in Period III. Despite these variations, methane emissions normalized per active longwall panel remained relatively stable, indicating a consistent emission intensity associated with individual production units. This suggests that total emission variability at the shaft scale is primarily driven by changes in mining activity rather than intrinsic variations in gas release per longwall.

The total annual methane release from the ventilation shaft was estimated at $10.7 \pm 0.93 \text{ kt CH}_4 \cdot \text{yr}^{-1}$, with seasonal variability resulting in ~48% lower emissions during summer compared to winter conditions. Statistically significant correlations were observed between methane emissions and both longwall advance ($R^2 \approx 0.55$, $p < 0.05$) and coal production ($R^2 \approx 0.38$, $p < 0.05$). These relationships demonstrate that CH_4 release at the shaft level is closely linked to operational mining parameters. Relationships between methane concentration, methane emission, and key operational parameters, including coal production and longwall advance, are summarized in Fig. 15.





460 **Figure 15: Relationships between CH₄ concentration and emission and key operational parameters. Data are aggregated into consecutive 10-day periods corresponding to the mine reporting system, in which coal production and longwall advance are routinely recorded at 10-day intervals. Panels (a) and (b) show correlations between methane concentration and emission and longwall advance, coal production, and combined output. Panels (c) and (d) present time series of methane emission compared with coal production and longwall progress, illustrating the temporal coupling between methane release and mining activity.**

465 The results indicate clear positive correlations between methane concentration and emission and mining activity indicators, with stronger relationships observed for emission than for concentration. Time series analysis further demonstrates that methane emission dynamics closely follow variations in mining activity, although short-term deviations are also evident. Overall, the monthly differences in methane release substantially exceeded short-term daily variability, demonstrating that short-duration monitoring campaigns may significantly under- or overestimate annual CH₄ emissions if seasonal variability

470 is not fully represented.

5 Discussion

5.1 Controls on methane variability in the ventilation system

Methane emissions from underground coal mining represent a significant component of anthropogenic greenhouse gas emissions (represent 33% of total fossil-fuel-related emissions, Saunio et al., 2025), and improving their quantification is

475 essential for accurate emission inventories and effective mitigation strategies. The results of this study demonstrate that CH₄ variability in the ventilation shaft is primarily controlled by the intensity of methane release from underground coal workings, while ventilation airflow acts mainly as a secondary dilution mechanism. This conclusion is supported by greater variability of methane concentrations compared to airflows and by the occurrence of concentration peaks that are unrelated to ventilation intensities. Temporal patterns observed at seasonal, weekly, and diurnal scales indicate that methane variability

480 is strongly linked to mining activity. Elevated CH₄ levels during periods of intensified production and their decline following reduction in the number of active longwall panels confirm the dominant role of operational factors. As illustrated in Fig. 15, methane concentration and emission are strongly linked to mining activity, with consistent positive correlations observed across different operational parameters.

These observations are consistent with previous studies showing that methane release rates in underground coal mines reflect

485 geological conditions, mining methods, and stress redistribution in the rock mass (Karacan et al., 2011; Swolkień, 2020). More recent studies confirm that this variability is evident across multiple spatial and temporal scales. For example, facility-scale satellite observations by Li et al. (2025) showed that CH₄ plume dynamics in Chinese coal mines are strongly controlled by coal rank, and production stage, with higher emissions typically associated with bituminous coal operations. Similarly, Karacan et al. (2025), using high-frequency measurements in underground coal mines in southwestern Virginia

490 (USA), demonstrated that changes in CH₄ concentrations at ventilation shafts are primarily related to production rate, geological conditions (or coal seam geological characteristics – to be precise), and residual gas content following degasification.



Longwall mining in particular enhances methane liberation through fracture propagation and degassing of gob areas (Mahdevari, 2019; Swolkień and Szlązak, 2020). Episodic CH₄ peaks observed in this study are therefore attributed to transient gas release events related to longwall advance, roof deformation, or variations in gas drainage efficiency (Szlązak et al., 2022; Schatzel et al., 2017; Boger et al., 2014). At shorter timescales, diurnal variability reflects the mining schedule, with methane CH₄ increasing shortly after the start of production shifts. The observed delay of ~1.5 h corresponds to gas transport time within the ventilation network and is consistent with previous high-frequency studies (Karacan et al., 2025). Over longer timescales, methane emission trends are influenced by the transition to deeper seams with higher gas content, as well as by modifications in ventilation and degassing systems (Zhang et al., 2023; Dreger and Kędzior, 2019; Kholod et al., 2020). Overall, CH₄ concentration measured at the shaft represents an integrated signal of emission processes across multiple production zones rather than a direct function of ventilation variability alone.

5.2 Role of ventilation and implications for emission quantification

The inverse relationship between methane concentration and ventilation airflow confirms the role of ventilation systems as a dilution mechanism. However, this relationship is non-stationary and varies with operational conditions. Periods of negative correlation reflect ventilation-controlled regimes, whereas weaker or positive correlations indicate enhanced methane inflow from underground sources. This behavior highlights the coupled nature of CH₄ release and ventilation dynamics. Increased airflow reduces methane concentration through dilution but can simultaneously enhance gas transport from production zones by modifying pressure gradients and flow distribution (McPherson, 2009; Mahdevari, 2019; Karacan et al., 2011). Consequently, CH₄ concentration dynamics cannot be interpreted solely as a function of airflow intensity. An important implication is that CH₄ emission expressed as mass flux does not necessarily decrease with increasing airflow, as it depends on both concentration and volumetric flow rate. Similar findings have been reported in previous studies, which show that short-term variations in ventilation conditions can significantly influence emission estimates (Swolkień et al., 2022; Dreger, 2020).

Furthermore, episodic methane release events and transient peaks are often not fully captured in inventory-based approaches, which rely on averaged data. In contrast, long-term continuous datasets provide more stable and representative emission estimates, reducing uncertainty associated with short-term variability (Swolkień et al., 2022; Luther et al., 2019). Evidence from major coal-producing regions such as China, India, and Turkey also demonstrates the significant role of mine ventilation systems in controlling CH₄ release worldwide, with emission rates strongly influenced by geological conditions, mining practices, and production intensity (Gao et al., 2020; Singh and Mallick, 2015; Mishra et al., 2016; Uyar and Akcin, 2025). These results confirm that high-resolution continuous monitoring is essential for reliable methane emission assessment at the mine scale.



5.3 Performance of methane monitoring systems

The comparison between the TDLAS-based Axetris analyser and the pellistor sensor demonstrates that both instruments captured the major temporal patterns of methane variability, including seasonal and diurnal trends. However, the dominant discrepancy between the systems was a systematic calibration bias, manifested as a persistent underestimation of methane concentrations by the pellistor sensor. Differences in dynamic response and temporal smoothing of short-term peaks were also observed, but these effects were secondary compared to the calibration offset. This interpretation is supported by the substantial improvement in agreement after recalibration, with the coefficient of determination increasing from 0.18 to 0.93. Such calibration biases may originate from routine maintenance practices, ageing of catalytic elements, drift between calibration intervals, or differences between calibration and operational conditions. Response non-linearity and delayed sensor response may additionally contribute to residual disagreement, particularly during rapidly changing methane concentrations (Bíró et al., 2017; Gawor and Wasilewski, 2021; Kumar et al., 2013). Similar discrepancies between high-resolution optical measurements and conventional mine monitoring systems have been reported in previous studies (Nęcki et al., 2026; Swolkień et al., 2022). After calibration, agreement between the two systems improves, confirming that pellistor sensors can provide reliable data when properly corrected. However, residual deviations remained particularly at concentration extremes and during periods characterized by rapid methane variability.

From an engineering perspective, these findings indicate that existing monitoring infrastructure can be significantly improved through integration with high-resolution optical instruments. Such hybrid measurement approaches provide a practical pathway toward improved methane emission quantification while maintaining operational feasibility. While pellistor sensors require careful calibration due to catalyst ageing and slower dynamic response, optical sensing technologies offer superior stability, faster response, and lower long-term uncertainty. For example, Zhang et al. (2025) demonstrated that Fourier Transform Infrared (FTIR) spectroscopy enables highly selective CH₄ quantification in complex gas mixtures, achieving detection limits as low as 0.5 ppm and an absolute error below 0.3% of full scale. Likewise, Wu et al. (2022) reported that TDLAS sensors provide high accuracy (0.06%) and sensitivity (25 ppm), along with rapid response and strong operational stability in coal mine environments. Redundant non-dispersive infrared (NDIR) sensors used by Karacan et al. (2025) enabled continuous monitoring of ventilation shaft air with improved stability at low CH₄ concentrations (0.5–2.0%), typical of ventilation air. Similarly, laser-based systems, such as open-path TDLAS analyzers, offer higher analytical precision, faster response times, and lower long-term uncertainty under variable ventilation conditions (Nęcki et al., 2026).

5.4 Comparison with emission inventories: EDGAR and E-PRTR

The results of this study were evaluated against independent methane emission estimates derived from both global and facility-level inventories, including the EDGAR database (European Commission, 2019) and the European Pollutant Release and Transfer Register (E-PRTR) (European Commission, 2006). The EDGAR database provides globally consistent emissions based on standardized methodologies and activity data, reported on a gridded scale ($\sim 0.1^\circ \times 0.1^\circ$) (Scarpelli et al.,



2020; Crippa et al., 2020). For coal mining regions such as the Upper Silesian Coal Basin, EDGAR-based estimates suggest typical ventilation-shaft emissions of 6–10 kt CH₄·yr⁻¹. Although such estimates reflect the overall magnitude of emissions, they smooth spatial variability and do not capture transient emission peaks.

In contrast, E-PRTR provides facility-level emissions reported by operators based on production data and emission factors. For the Chwałowice coal mine, reported methane emission is ~12.1 kt CH₄·yr⁻¹ (WUG Poland, 2026). The annual methane emission determined in this study (10.7 ± 0.93 kt CH₄·yr⁻¹) is comparable to facility-level estimates reported through E-PRTR and lies close to the upper range of ventilation-shaft emissions inferred from EDGAR-based products for the Upper Silesian Coal Basin. Although the agreement is not exact, the comparison indicates that major inventory frameworks capture the correct order of magnitude of methane emissions from underground coal mining. At the same time, the measured value is higher than EDGAR-derived estimates, reflecting the effect of spatial averaging and temporal smoothing in gridded inventories. The comparison highlights the complementary nature of inventory- and measurement-based approaches. Bottom-up inventories provide long-term and regionally consistent emission estimates, whereas continuous in-situ measurements resolve site-specific variability that is generally not represented in inventory products. Together, these approaches improve understanding and quantification of methane emissions from coal mining systems.

Similar methane emission magnitudes have been reported previously for individual ventilation shafts and mining facilities within the Upper Silesian Coal Basin (Luther et al., 2019). Regional atmospheric studies further demonstrate that inventory-based approaches generally reproduce basin-scale emissions (Kostinek et al., 2021), although direct in-shaft measurements remain essential for quantifying temporal variability and evaluating operational controls on methane release.

5.5 Emission factors and global context

Accurate identification emission estimation and reliable determination of emission factors (EFs) are essential for improving regional methane inventories, constraining the atmospheric CH₄ budget, and supporting effective mitigation strategies. The emission factor derived in this study (5.1 ± 1.0 m³ CH₄·t⁻¹) falls within the lower range of values reported for underground coal mines, but remains consistent with both national and international datasets. The emission factors reported for the Upper Silesian Coal Basin vary between 5 and 15 m³ CH₄·t⁻¹, depending on the data source and methodology (see Supplement, Table S1). Amount of emitted CH₄ from one ton of mined coal determined in this study is comparable to EFs of low-to medium-gassiness coal mines in Poland, such as the PGG Halemba coal mine (7.5 m³ CH₄·t⁻¹) and JSW Budryk coal mine (10.0 m³ CH₄·t⁻¹) (WUG Poland, 2026). According to Dreger and Kędzior (2019) methane emission factor in Polish coal mines ranged from 5.7 to 15.2 m³ CH₄·t⁻¹ coal between 1997 and 2016, indicating a progressive increase in emission intensity over time associated with mining advancement into deeper and more methane-rich seams.

The methane emission factor derived in this study (5.1 ± 1.0 m³ CH₄·t⁻¹) lies within the range reported for underground coal mines in the Upper Silesian Coal Basin and elsewhere worldwide (see Supplement, Table S1). Although it is located toward the lower end of the reported range, it is consistent with values observed for low- to medium-gassiness mines in Poland. The agreement between measurement-derived and inventory-derived emission factors supports the use of production-based



emission factors for long-term methane reporting, while emphasizing the value of continuous observations for resolving temporal variability. According to the IPCC Tier 1 methodology, methane emission factors varied from 10 to 25 m³ CH₄·t⁻¹ coal for mines about 400 m deep (see Supplement, Table S2), reflecting differences in seam depth, gas content, and mining conditions (IPCC, 2006). Comparable variability in methane emissions has been documented worldwide. Studies from China, India, Canada, Australia and Turkey show that methane emission rates vary significantly between mines due to differences in geological conditions, extraction depth, and production characteristics (Gao et al., 2020; Singh et al., 2015; Singh et al., 2022; Rend et al., 2023; CMM Country Profiles, 2015; Sadavarte et al., 2021). Long-term trends also indicate that methane emissions may increase despite declining coal production, primarily due to mining at greater depths and in methane-rich seams (Kholod et al., 2020; Chen et al., 2024).

One of the most important findings of this study is that methane emissions were more strongly correlated with longwall advance than with coal production. This suggests that the progression of the mining front provides a more direct representation of methane release processes than production tonnage alone. While coal production reflects extraction intensity, it does not explicitly account for geological heterogeneity, fracture development, stress redistribution, or methane liberation from adjacent strata. In contrast, longwall advance is more directly linked to the physical processes controlling gas release. Regression analysis of decadal CH₄ emissions against longwall cross-sectional progress yielded an emission factor of 13.4 ± 2.4 m³ CH₄·m⁻² of longwall progression, demonstrating a robust relationship between mining geometry and methane release. This factor reflects methane emissions associated with the advance of 2–4 active longwall panels operated during the study period (see Supplement, Table S3). These findings support the development of improved emission factors that incorporate both production and geometrical parameters, consistent with recent recommendations in emission inventory methodologies (Gao et al., 2020; EMEP, 2023).

Importantly, the consistency between the emission factor determined in this study and those reported in large-scale inventories (see Supplement, Table S2) demonstrates that emission factors used in national and global databases are not purely theoretical constructs, but reflect real CH₄ release processes occurring in underground mines. This agreement supports the validity of inventory-based approaches, while also highlighting the added value of high-resolution measurements for capturing temporal variability and refining emission factors at the site level. Moreover, to reduce the uncertainty of EFs, specific CH₄ emission intensities should be developed separately for each mine and operational scenarios because contributors to gas release differ between mining regions, depending on covered timescales and coal production (Karacan et al., 2011; Zhang et al., 2025).

5.6 Implications for emission reporting, mitigation and future work

The results demonstrate that continuous high-resolution CH₄ monitoring can be used to improve emission estimates compared with conventional inventory methods based on static emission factors. The observed variability reveals that short-term measurements may lead to systematic bias in emission inventories if seasonal and operational patterns are not fully represented. This has direct implications for emerging regulatory frameworks, including the European Union Methane



Regulation (EU) 2024/1787, which emphasizes measurement-based reporting (Official Journal of the European Union, 2024). High-resolution datasets provide a robust basis for improving emission inventories and reducing uncertainty while improving safety.

From a mitigation perspective, methane emission is strongly linked to mining activity, indicating that emission reduction strategies should be integrated with operational data. Effective mitigation approaches include optimization of methane drainage systems and implementation of ventilation air methane utilization technologies (Karacan et al., 2011; Lan et al., 2018). The applicability and performance of methane mitigation technologies will be strongly influenced by ventilation conditions, including airflow rate, temporal variability in CH₄ concentration, humidity, dust loading, and the presence of contaminants (e.g., H₂S, SO_x) in the ventilation air (Iwaniszyn et al., 2025; UNECE, 2005; Liu et al., 2023).

The temporal patterns of methane, airflow rates, and production-related emissions estimated in this study may support forecasting of elevated-emission periods. The ability to identify periods of elevated CH₄ emissions provides a basis for adaptive emission control strategies, enabling more efficient methane management in underground coal mines. The temporal patterns (see Fig. 15) demonstrate that CH₄ emissions reflect mining activities, supporting the implementation of adaptive monitoring and mitigation strategies based on real-time operational data.

This study is based on measurements from a single ventilation shaft and may not fully represent variability across different mines or geological conditions. Previous studies have demonstrated substantial differences in methane emission intensity between mines within the same basin (Zięba and Smoliński, 2025; Swolkień, 2020). Uncertainty in emission estimates is dominated by airflow measurements, which are affected by turbulence and non-uniform flow conditions. Similar limitations have been reported in previous studies (Swolkień et al., 2022; Zazzeri et al., 2016).

Future work should focus on improving airflow measurements and extending monitoring to multiple shafts and mines. Integration with computational fluid dynamics (CFD) modelling and atmospheric observations (e.g., UAV or satellite data) will further improve understanding of CH₄ transport processes and support development of more accurate emission inventories (Kostinek et al., 2021; Andersen et al., 2023). Future studies should evaluate the temporal stability of calibration relationships between optical and catalytic sensors and assess optimal recalibration intervals using drift-detection approaches. Additionally, future studies should evaluate measurement reproducibility across different ventilation configurations and geological settings to establish the broader applicability of emission factors and facilitate their transfer to other mining sites.

6 Conclusions

This study presents a comprehensive one-year dataset of high-resolution methane measurements in a coal mine ventilation shaft, providing new insight into methane emission dynamics under real operating conditions. The results show that CH₄ variability is primarily controlled by mining activity, particularly longwall advance and production intensity, while



ventilation airflow acts mainly as a dilution mechanism. Short-term methane fluctuations are driven by transient emission processes and are not fully captured by conventional monitoring systems or inventory approaches.

The comparison between TDLAS and pellistor sensors demonstrates that standard mine monitoring systems underestimate CH₄ concentration variability and require improved and regular calibration for quantitative emission analysis. Recalibration of Pellistor data using Axetris measurements significantly improved agreement between the two systems (reducing the relative RMSE to ~7%) and confirming the importance of regular drift correction for long-term monitoring applications. Integration of high-precision optical instruments significantly improves measurement accuracy and enables reliable long-term monitoring.

The direct assessment of CH₄ emissions revealed substantial temporal variability, primarily controlled by seasonal and mining-operational factors rather than short-term daily fluctuations. At the annual scale, methane emissions exhibited a cyclic pattern linked to the progression of coal extraction activities. Maximum emissions were recorded during the pre-winter period of intensified mining operations. Despite the overall decrease in total CH₄ emissions, values normalized to the number of active longwall panels remained relatively stable, indicating a consistent gas release intensity at the panel scale.

Methane emissions derived in this study are consistent with both global (EDGAR) and facility-level (E-PRTR) emission inventories, demonstrating that these databases provide realistic estimates of methane emissions when interpreted at the appropriate scale. Annual CH₄ emissions from the monitored ventilation shaft were estimated at 10.7 ± 0.93 kt CH₄·yr⁻¹, a value comparable to those reported for low- to medium-gassiness coal mines in Poland. The close agreement between direct measurements and inventory estimates indicates that inventory- and measurement-based approaches are complementary rather than contradictory.

The site-specific methane emission factor determined in this study was 5.1 ± 1.0 m³ CH₄·t⁻¹ of extracted coal, remaining consistent with both national and international datasets. Moreover, regression analysis identified a mining-front progression factor of 13.4 ± 2.4 m³ CH₄·m⁻² of longwall advance, highlighting the strong relationship between the geometric development of mining panels and gas release. The study further demonstrates that emission factors based solely on coal production may not fully capture methane release processes, and that longwall advance provides a more representative parameter for emission modelling.

Overall, the results highlight the importance of continuous high-resolution measurements for improving methane emission inventories, reducing uncertainty, and supporting effective mitigation strategies in underground coal mining. In addition, the high-resolution continuous CH₄ datasets generated in this and future studies will provide valuable reference data for the validation of satellite observations, atmospheric inversion models, and methane retrieval algorithms in coal mining regions.

Supplement

The link to the supplement will be included by Copernicus.



Author contributions

YB: Conceptualization, Methodology, Formal analysis, Data collection, Investigation, Writing – original draft, Review & Editing, Visualization, Final shaping, Supervision, Project administration, Funding acquisition. AG: Data curation, Visualization, Writing – review & editing. DS: Methodology, Writing – review & editing. JB: Methodology, Writing – review & editing. PJ: Data collection, Writing – review & editing. JS: Data curation, Writing – review & editing. MG: Data curation, Writing – review & editing. RF: Project Supervision, Funding acquisition, Writing – review & editing. JN: Writing – Formal analysis, Rewriting, Editing, Final shaping.

Competing interests

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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Review statement

- 710 The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

References

- Andersen, T., Zhao, Z., de Vries, M., Necki, J., Swolkien, J., Menoud, M., Röckmann, T., Roiger, A., Fix, A., Peters, W., and Chen, H.: Local-to-regional methane emissions from the Upper Silesian Coal Basin (USCB) quantified using UAV-based atmospheric measurements, *Atmos. Chem. Phys.*, 23, 5191–5216, <https://doi.org/10.5194/acp-23-5191-2023>, 2023.
- 715 WUG Poland (State Mining Authority). Methane emission reports 2025: <https://wug.bip.info.pl/dokument,iddok,923,idmp,60,r,r>, last access: 10 May 2026.
- Axetris LGD Compact-A CH₄: <https://www.axetris.com/en-jp/product/LGD-Compact-A-CH4#product-description>, last access: 19 December 2025.
- 720 Bezyk, Y., Szurgacz, D., Górka, M., Strapoć, D., Kruszewski, Ł., Wachniew, P., Nęcki, J., Zimnoch, M., Sówka, I., Modelska, M., Wołkowicz, W., van der Veen, C., and Röckmann, T.: Isotope and chemical alteration of coalbed gases during migration from underground coal mine into the atmosphere, *Int. J. Coal Geol.*, 104922, <https://doi.org/10.1016/j.coal.2025.104922>, 2025.
- Bíró, F., Dücső, C., Radnóczy, G. Z., Baji, Z., Takács, M., and Bársony, I.: ALD nano-catalyst for micro-calorimetric detection of hydrocarbons, *Sensors Actuators B Chem.*, 247, 617–625, <https://doi.org/10.1016/j.snb.2017.03.075>, 2017.
- 725 Boger, C., Marshall, J. S., and Pilcher, R. C.: Worldwide Coal Mine Methane and Coalbed Methane Activities, in: *Coal Bed Methane*, Elsevier, 351–407, <https://doi.org/10.1016/B978-0-12-800880-5.00018-8>, 2014.
- Brodny, J., Felka, D., and Tutak, M.: Applying an Automatic Gasometry System and a Fuzzy Set Theory to Assess the State of Gas Hazard during the Coal Mining Production Process, *Eng. Sci.*, <https://doi.org/10.30919/es891>, 2023.
- 730 Chen, D., Ma, M., Hu, L., Du, Q., Li, B., Yang, Y., Guo, L., Cai, Z., Ji, M., Zhu, R., and Fang, X.: Characteristics of China's coal mine methane emission sources at national and provincial levels, *Environ. Res.*, 259, 119549, <https://doi.org/10.1016/j.envres.2024.119549>, 2024.
- CMM Country Profiles. Canada. Summary of Coal Industry. 2015. Available at: <https://www.globalmethane.org/coal/country-profiles.aspx>
- 735 Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., and Janssens-Maenhout, G.: High resolution temporal profiles in the Emissions Database for Global Atmospheric Research, *Sci. Data*, 7, 121, <https://doi.org/10.1038/s41597-020-0462-2>, 2020.
- Dreger, M.: Changes in the methane emissions and hard coal output in the Brzeszcze mine (the Upper Silesian Coal Basin, Poland), *Geol. Geophys. Environ.*, 46, 159, <https://doi.org/10.7494/geol.2020.46.2.159>, 2020.



- 740 Dreger, M. and Kędzior, S.: Methane emissions and demethanation of coal mines in the Upper Silesian Coal Basin between 1997 and 2016, *Environ. Socio-economic Stud.*, 7, 12–23, <https://doi.org/10.2478/environ-2019-0002>, 2019.
EMEP: EEA air pollutant emission inventory guidebook, 2023.
European Commission: European Pollutant Release and Transfer Register (E-PRTR): <https://eur-lex.europa.eu/EN/legal-content/summary/european-pollutant-release-and-transfer-register-e-prtr.html>, last access: 20 December 2025.
- 745 European Commission: Emission Database for Global Atmospheric Research (EDGAR), release version 5: https://edgar.jrc.ec.europa.eu/dataset_ghg60, last access: 20 December 2025.
Fiehn, A., Eckl, M., Kostinek, J., Gałkowski, M., Gerbig, C., Rothe, M., Röckmann, T., Menoud, M., Maazallahi, H., Schmidt, M., Korbeń, P., Nečki, J., Stanisavljević, M., Swolkień, J., Fix, A., and Roiger, A.: Source apportionment of methane emissions from the Upper Silesian Coal Basin using isotopic signatures, *Atmos. Chem. Phys.*, 23, 15749–15765, <https://doi.org/10.5194/acp-23-15749-2023>, 2023.
- 750 Förster, E., Huntrieser, H., Lichtenstern, M., Pätzold, F., Bretschneider, L., Schlerf, A., Bollmann, S., Lampert, A., Nečki, J., Jagoda, P., Swolkień, J., Pasternak, D., Field, R. A., and Roiger, A.: A helicopter-based mass balance approach for quantifying methane emissions from industrial activities, applied for coal mine ventilation shafts in Poland, <https://doi.org/10.5194/egusphere-2025-1010>, 12 March 2025.
- 755 Gałkowski, M., Jordan, A., Rothe, M., Marshall, J., Koch, F.-T., Chen, J., Agusti-Panareda, A., Fix, A., and Gerbig, C.: In situ observations of greenhouse gases over Europe during the CoMet 1.0 campaign aboard the HALO aircraft, *Atmos. Meas. Tech.*, 14, 1525–1544, <https://doi.org/10.5194/amt-14-1525-2021>, 2021.
Gao, J., Guan, C., and Zhang, B.: China’s CH₄ emissions from coal mining: A review of current bottom-up inventories, *Sci. Total Environ.*, 725, 138295, <https://doi.org/10.1016/j.scitotenv.2020.138295>, 2020.
- 760 Gao, Q., Zhang, Y., Yu, J., Wu, S., Zhang, Z., Zheng, F., Lou, X., and Guo, W.: Tunable multi-mode diode laser absorption spectroscopy for methane detection, *Sensors Actuators A Phys.*, 199, 106–110, <https://doi.org/10.1016/j.sna.2013.05.012>, 2013.
Gawor, M. and Wasilewski, S.: Investigations of dynamic properties of an integrated methane and rock outburst sensor, *Measurement*, 186, 110178, <https://doi.org/10.1016/j.measurement.2021.110178>, 2021.
- 765 Goodman, G. V. R., Karacan, C. Ö., Schatzel, S. J., Krog, R. B., Taylor, C. D., and Thimons, E. D.: NIOSH research for monitoring and controlling methane at U.S. underground coal mining operation, 2008.
Heltzel, R., Johnson, D., Zaki, M., Gebreslase, A., and Abdul-Aziz, O. I.: Understanding the Accuracy Limitations of Quantifying Methane Emissions Using Other Test Method 33A, *Environments*, 9, 47, <https://doi.org/10.3390/environments9040047>, 2022.
- 770 IPCC: Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, Chapter 4: Fugitive Emissions., 2006.
Iwaniszyn, M., Pawlaczyk-Kurek, A., Kołodziej, A., Rotkegel, A., Tańczyk, M., Skiba, J., Hildebrandt, R., Bałaga, D., Siegmund, M., and Gancarczyk, A.: Ventilation Air Methane (VAM) Utilisation: Comparison of the Thermal and Catalytic Oxidation Processes, *Energies*, 18, 1428, <https://doi.org/10.3390/en18061428>, 2025.



- Jiang, J., Zhao, M., Ma, G.-M., Song, H.-T., Li, C.-R., Han, X., and Zhang, C.: TDLAS-Based Detection of Dissolved Methane in Power Transformer Oil and Field Application, *IEEE Sens. J.*, 18, 2318–2325, <https://doi.org/10.1109/JSEN.2017.2788871>, 2018.
- Jureczka, J., Dopita, M., Gałka, M., Krieger, W., Kwarciński, J., Martinec, P.: Geological Atlas of Coal Deposits of the Polish and Czech Parts of the Upper Silesian Coal Basin. Polish Geological Institute, Polish Geol. Inst., 31 pp., 2005.
- Karacan, C. Ö., Ruiz, F. A., Cotè, M., and Phipps, S.: Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction, *Int. J. Coal Geol.*, 86, 121–156, <https://doi.org/10.1016/j.coal.2011.02.009>, 2011.
- Karacan, C. Ö., Irakulis-Loitxate, I., Field, R. A., and Warwick, P. D.: Temporal and spatial comparison of coal mine ventilation methane emissions and mitigation quantified using PRISMA satellite data and on-site measurements, *Sci. Total Environ.*, 975, 179268, <https://doi.org/10.1016/j.scitotenv.2025.179268>, 2025.
- Kędzior, S. and Dreger, M.: Geological and Mining Factors Controlling the Current Methane Conditions in the Rydułtowy Coal Mine (Upper Silesian Coal Basin, Poland), *Energies*, 15, 6364, <https://doi.org/10.3390/en15176364>, 2022.
- Kędzior, S. and Dreger, M.: Time variability of methane extraction from hard coal deposits in the Upper Silesian Coal Basin (Poland) in relation to geological and mining conditions, *J. Sustain. Min.*, 22, 89–99, <https://doi.org/10.46873/2300-3960.1379>, 2023.
- Kholod, N., Evans, M., Pilcher, R. C., Roshchanka, V., Ruiz, F., Coté, M., and Collings, R.: Global methane emissions from coal mining to continue growing even with declining coal production, *J. Clean. Prod.*, 256, 120489, <https://doi.org/10.1016/j.jclepro.2020.120489>, 2020.
- Knapp, M., Scheidweiler, L., Külheim, F., Kleinschek, R., Necki, J., Jagoda, P., and Butz, A.: Spectrometric imaging of sub-hourly methane emission dynamics from coal mine ventilation, *Environ. Res. Lett.*, 18, 044030, <https://doi.org/10.1088/1748-9326/acc346>, 2023.
- Kostinek, J., Roiger, A., Eckl, M., Fiehn, A., Luther, A., Wildmann, N., Klausner, T., Fix, A., Knote, C., Stohl, A., and Butz, A.: Estimating Upper Silesian coal mine methane emissions from airborne in situ observations and dispersion modeling, *Atmos. Chem. Phys.*, 21, 8791–8807, <https://doi.org/10.5194/acp-21-8791-2021>, 2021.
- Krause, E. and Krzemień, K.: Methane Risk Assessment in Underground Mines by Means of a Survey by the Panel of Experts (Sope), *J. Sustain. Min.*, 13, 6–13, <https://doi.org/10.7424/jsm140202>, 2014.
- Krzeszowska, E.: Chemostratigraphic Approach to the Study of Resources' Deposit in the Upper Silesian Coal Basin (Poland), *Energies*, 17, 642, <https://doi.org/10.3390/en17030642>, 2024.
- Kumar A., Kingson T.M.G., Verma R.P., Kumar A., Mandal R., Dutta S., Chaulya S.K., P. G. M.: Application of Gas Monitoring Sensors in Underground Coal Mines and Hazardous Areas, *Int. J. Comput. Technol. Electron. Eng.*, 3, 9–23, 2013.



- Lan, B., Li, Y.-R., Zhao, X.-S., and Kang, J.-D.: Industrial-Scale Experimental Study on the Thermal Oxidation of Ventilation Air Methane and the Heat Recovery in a Multibed Thermal Flow-Reversal Reactor, *Energies*, 11, 1578, <https://doi.org/10.3390/en11061578>, 2018.
- Li, X., Cheng, T., Zhu, H., Ye, X., Fan, D., Tang, T., Tong, H., Yin, S., and Xiong, J.: High-Resolution Satellite Reveals the Methane Emissions from China's Coal Mines, *Remote Sens.*, 17, 220, <https://doi.org/10.3390/rs17020220>, 2025.
- Liang, Y., Tang, X., Zhang, X., Tian, F., Sun, Y., and Dong, H.: Portable Gas Analyzer Based on Fourier Transform Infrared Spectrometer for Patrolling and Examining Gas Exhaust, *J. Spectrosc.*, 2015, 1–7, <https://doi.org/10.1155/2015/136516>, 2015.
- Liu, Z., Xu, B., Jiang, Y.-J., Zhou, Y., Sun, X., Wang, Y., and Zhu, W.: Photocatalytic Conversion of Methane: Current State of the Art, Challenges, and Future Perspectives, *ACS Environ. Au*, 3, 252–276, <https://doi.org/10.1021/acsenvironau.3c00002>, 2023.
- Luther, A., Kleinschek, R., Scheidweiler, L., Defratyka, S., Stanisavljevic, M., Forstmaier, A., Dandocsi, A., Wolff, S., Dubravica, D., Wildmann, N., Kostinek, J., Jöckel, P., Nickl, A.-L., Klausner, T., Hase, F., Frey, M., Chen, J., Dietrich, F., Nęcki, J., Swolkień, J., Fix, A., Roiger, A., and Butz, A.: Quantifying CH₄ emissions from hard coal mines using mobile sun-viewing Fourier transform spectrometry, *Atmos. Meas. Tech.*, 12, 5217–5230, <https://doi.org/10.5194/amt-12-5217-2019>, 2019.
- Mahdevari, S.: Coal mine methane: Control, utilization, and abatement, in: *Advances in Productive, Safe, and Responsible Coal Mining*, Elsevier, 179–198, <https://doi.org/10.1016/B978-0-08-101288-8.00010-9>, 2019.
- McPherson, M.: *Subsurface Ventilation Engineering*, University of California, 2009.
- Menoud, M., van der Veen, C., Necki, J., Bartyzel, J., Szénási, B., Stanisavljević, M., Pison, I., Bousquet, P., and Röckmann, T.: Methane (CH₄) sources in Krakow, Poland: insights from isotope analysis, *Atmos. Chem. Phys.*, 21, 13167–13185, <https://doi.org/10.5194/acp-21-13167-2021>, 2021.
- Mishra, D. P., Kumar, P., and Panigrahi, D. C.: Dispersion of methane in tailgate of a retreating longwall mine: a computational fluid dynamics study, *Environ. Earth Sci.*, 75, 475, <https://doi.org/10.1007/s12665-016-5319-9>, 2016.
- Morrison, F. A.: *Uncertainty Analysis for Engineers and Scientists*, Cambridge University Press, <https://doi.org/10.1017/9781108777513>, 2020.
- Nęcki, J. M., Bartyzel, J., Jagoda, P., Swolkień, J., Szlązak, N., Korzec, M., Butler, N., Łukańko, Ł., and Field, R. A.: Evaluating Pellistor sensors for reporting of methane emission in coal mine ventilation: Toward low-cost reporting solutions, *Measurement*, 265, 120385, <https://doi.org/10.1016/j.measurement.2026.120385>, 2026.
- Nickl, A.-L., Mertens, M., Roiger, A., Fix, A., Amediek, A., Fiehn, A., Gerbig, C., Galkowski, M., Kerkweg, A., Klausner, T., Eckl, M., and Jöckel, P.: Hindcasting and forecasting of regional methane from coal mine emissions in the Upper Silesian Coal Basin using the online nested global regional chemistry–climate model MECO(n) (MESSy v2.53), *Geosci. Model Dev.*, 13, 1925–1943, <https://doi.org/10.5194/gmd-13-1925-2020>, 2020.



- Official Journal of the European Union: Regulation (EU) 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942, 2024.
- Pierchala, A. and Czuga, P.: Way of venting the Chwalowice main from Donnersmarck-Grubbe to PGG S.A. ROW coal mine in the Chwalowice mining region, in: Systems Supporting Production Engineering, 252–262, 2019.
- Poch, J. and Villaescusa, I.: Orthogonal Distance Regression: A Good Alternative to Least Squares for Modeling Sorption Data, *J. Chem. Eng. Data*, 57, 490–499, <https://doi.org/10.1021/je201070u>, 2012.
- Ralston, J. C., Reid, D. C., Dunn, M. T., and Hainsworth, D. W.: Longwall automation: Delivering enabling technology to achieve safer and more productive underground mining, *Int. J. Min. Sci. Technol.*, 25, 865–876, <https://doi.org/10.1016/j.ijmst.2015.09.001>, 2015.
- Rend, A. R., Özer, S. C., Esen, O., Soylu, A., Bozdoğan, S., and Fişne, A.: Developing basin-specific emission factors for accurate methane inventory and emission reduction strategies in Zonguldak Coal Basin, Turkey: Implications for enhancing safety and sustainability, *J. Clean. Prod.*, 426, 139177, <https://doi.org/10.1016/j.jclepro.2023.139177>, 2023.
- Sadavarte, P., Pandey, S., Maasackers, J. D., Lorente, A., Borsdorff, T., Denier van der Gon, H., Houweling, S., and Aben, I.: Methane Emissions from Superemitting Coal Mines in Australia Quantified Using TROPOMI Satellite Observations, *Environ. Sci. Technol.*, 55, 16573–16580, <https://doi.org/10.1021/acs.est.1c03976>, 2021.
- Saki, S. A.: CFD study of the effect of face ventilation on CH₄ in returns and explosive gas zones in progressively sealed longwall gobs, *J. South. African Inst. Min. Metall.*, 117, 257–262, <https://doi.org/10.17159/2411-9717/2017/v117n3a7>, 2017.
- Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P. A., Regnier, P., Canadell, J. G., Jackson, R. B., Patra, P. K., Bousquet, P., Ciais, P., Dlugokencky, E. J., Lan, X., Allen, G. H., Bastviken, D., Beerling, D. J., Belikov, D. A., Blake, D. R., Castaldi, S., Crippa, M., Deemer, B. R., Dennison, F., Etiope, G., Gedney, N., Höglund-Isaksson, L., Holgersson, M. A., Hopcroft, P. O., Hugelius, G., Ito, A., Jain, A. K., Janardanan, R., Johnson, M. S., Kleinen, T., Krummel, P. B., Lauerwald, R., Li, T., Liu, X., McDonald, K. C., Melton, J. R., Mühle, J., Müller, J., Murguía-Flores, F., Niwa, Y., Noce, S., Pan, S., Parker, R. J., Peng, C., Ramonet, M., Riley, W. J., Rocher-Ros, G., Rosentreter, J. A., Sasakawa, M., Segers, A., Smith, S. J., Stanley, E. H., Thanwerdas, J., Tian, H., Tsuruta, A., Tubiello, F. N., Weber, T. S., van der Werf, G. R., Worthy, D. E. J., Xi, Y., Yoshida, Y., Zhang, W., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q.: Global Methane Budget 2000–2020, *Earth Syst. Sci. Data*, 17, 1873–1958, <https://doi.org/10.5194/essd-17-1873-2025>, 2025.
- Scarpelli, T. R., Jacob, D. J., Maasackers, J. D., Sulprizio, M. P., Sheng, J.-X., Rose, K., Romeo, L., Worden, J. R., and Janssens-Maenhout, G.: A global gridded (0.1° × 0.1°) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations Framework Convention on Climate Change, *Earth Syst. Sci. Data*, 12, 563–575, <https://doi.org/10.5194/essd-12-563-2020>, 2020.
- Schatzel, S. J., Krog, R. B., and Dougherty, H.: Methane emissions and airflow patterns on a longwall face: Potential influences from longwall gob permeability distributions on a bleederless longwall, *Transactions*, 342, 51–61, <https://doi.org/10.19150/trans.8108>, 2017.



- Sechman, H., Kotarba, M. J., Fiszer, J., and Dzieniewicz, M.: Distribution of methane and carbon dioxide concentrations in the near-surface zone and their genetic characterization at the abandoned “Nowa Ruda” coal mine (Lower Silesian Coal Basin, SW Poland), *Int. J. Coal Geol.*, 116–117, 1–16, <https://doi.org/10.1016/j.coal.2013.05.005>, 2013.
- Singh, H. and Mallick, J.: Utilization of Ventilation Air Methane in Indian Coal Mines: Prospects and Challenges, *Procedia Earth Planet. Sci.*, 11, 56–62, <https://doi.org/10.1016/j.proeps.2015.06.008>, 2015.
- Singh, S., Srichandan, H., Pathak, A., Gahan, C. S., Lee, S., Kim, D.-J., and Kim, B.-G.: Studies on the effect of coal particle size on biodepyritization of high sulfur coal in batch bioreactor, *Polish J. Chem. Technol.*, 17, 97–102, <https://doi.org/10.1515/pjct-2015-0014>, 2015.
- State Mining Authority: Assessment of the state of occupational safety, mine rescue and general safety in connection with mining and geological activities in 2024, Katowice, 2025.
- Su, S., Chen, H., Teakle, P., and Xue, S.: Characteristics of coal mine ventilation air flows, *J. Environ. Manage.*, 86, 44–62, <https://doi.org/10.1016/j.jenvman.2006.11.025>, 2008.
- Swolkień, J.: Polish underground coal mines as point sources of methane emission to the atmosphere, *Int. J. Greenh. Gas Control*, 94, 102921, <https://doi.org/10.1016/j.ijggc.2019.102921>, 2020.
- Swolkień, J. and Szlązak, N.: The Impact of the Coexistence of Methane Hazard and Rock-Bursts on the Safety of Works in Underground Hard Coal Mines, *Energies*, 14, 128, <https://doi.org/10.3390/en14010128>, 2020.
- Swolkień, J., Fix, A., and Gałkowski, M.: Factors influencing the temporal variability of atmospheric methane emissions from Upper Silesia coal mines: a case study from the CoMet mission, *Atmos. Chem. Phys.*, 22, 16031–16052, <https://doi.org/10.5194/acp-22-16031-2022>, 2022.
- Szlązak, N., Swolkień, J., and Kamiński, P.: Design of Coal Seam Exploitation in Methane Hazard Conditions: A Case Study, *Energies*, 16, 365, <https://doi.org/10.3390/en16010365>, 2022.
- Szurgacz, D., Tutak, M., Brodny, J., Sobik, L., and Zhironkina, O.: The Method of Combating Coal Spontaneous Combustion Hazard in Goafs—A Case Study, *Energies*, 13, 4538, <https://doi.org/10.3390/en13174538>, 2020.
- Tang, X., Liang, Y., Dong, H., Sun, Y., and Luo, H.: Analysis of Index Gases of Coal Spontaneous Combustion Using Fourier Transform Infrared Spectrometer, *J. Spectrosc.*, 2014, 1–8, <https://doi.org/10.1155/2014/414391>, 2014.
- Tian, F., Liang, Y., Zhu, H., Chen, M., and Wang, J.: Application of a novel detection approach based on non-dispersive infrared theory to the in-situ analysis on indicator gases from underground coal fire, *J. Cent. South Univ.*, 29, 1840–1855, <https://doi.org/10.1007/s11771-022-5006-9>, 2022.
- UNECE: Best Practice Guidance on Ventilation Air Methane (VAM) Mitigation. United Nations Economic Commission for Europe, Geneva, Switzerland., 2005.
- Uyar, N. and Akcin, H.: Investigation of Impact to Climate Change of Metan Emission of Underground Mines and Thermal Power Plants Using Sentinel-5p TROPOMI Satellite Data from GEE Platform, *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, XLVIII-M–6, 297–302, <https://doi.org/10.5194/isprs-archives-XLVIII-M-6-2025-297-2025>, 2025.
- Valoski, M. P.: Instruments for gas analysis at mine fires/explosions, pp. 10-039 pp., 2010.



- Wu, X., Cui, J., Tong, R., and Li, Q.: Research on Methane Measurement and Interference Factors in Coal Mines, *Sensors*, 22, 5608, <https://doi.org/10.3390/s22155608>, 2022.
- Wu, Z., Wang, Y., and Teng, F.: Building a mine-level database of methane emission factors for China's underground coal, *Environ. Res. Lett.*, 21, 024003, <https://doi.org/10.1088/1748-9326/ae3190>, 2026.
- Xu, S. and Chen, M.: Design and modeling of non-linear infrared transducer for measuring methane using cross-correlation method, *Measurement*, 45, 325–332, <https://doi.org/10.1016/j.measurement.2011.11.015>, 2012.
- Zazzeri, G., Lowry, D., Fisher, R. E., France, J. L., Lanoisellé, M., and Nisbet, E. G.: Plume mapping and isotopic characterisation of anthropogenic methane sources, *Atmos. Environ.*, 110, 151–162, <https://doi.org/10.1016/j.atmosenv.2015.03.029>, 2015.
- Zazzeri, G., Lowry, D., Fisher, R. E., France, J. L., Lanoisellé, M., Kelly, B. F. J., Necki, J. M., Iverach, C. P., Ginty, E., Zimnoch, M., Jasek, A., and Nisbet, E. G.: Carbon isotopic signature of coal-derived methane emissions to the atmosphere: from coalification to alteration, *Atmos. Chem. Phys.*, 16, 13669–13680, <https://doi.org/10.5194/acp-16-13669-2016>, 2016.
- Zhang, F., Zhu, Y., Li, L., Zhao, S., Zhang, X., and Chen, C.: Research on Quantitative Analysis Method of Infrared Spectroscopy for Coal Mine Gases, *Molecules*, 30, 3040, <https://doi.org/10.3390/molecules30143040>, 2025.
- Zhang, X., Zhu, T., Yi, N., Yuan, B., Li, C., Ye, Z., Zhu, Z., and Zhang, X.: Study on Characteristics and Model Prediction of Methane Emissions in Coal Mines: A Case Study of Shanxi Province, China, *Atmosphere (Basel)*, 14, 1422, <https://doi.org/10.3390/atmos14091422>, 2023.
- Zięba, M. and Smoliński, A.: Methane Emissions from Mining in the European Union, *Energies*, 18, 791, <https://doi.org/10.3390/en18040791>, 2025.