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Comparison of Production-Based and Direct Measurement Approaches for Estimating Methane Emissions from Underground Coal Mines

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ABSTRACT

Coal mine methane emissions are commonly estimated using emission factors linked to coal production or direct mine-scale measurements, corresponding to IPCC Tier 2 and Tier 3 methodologies, respectively. However, comparative evaluations of these bottom-up approaches remain limited, particularly for underground coal mining systems. Here, we compare monthly emission factor estimates with time-aligned direct measurements using a unique high-resolution industrial dataset from four underground coal mines in the Upper Silesian Coal Basin (Poland) for 2024. Results indicate that emission factor-based approaches introduce systematic bias and may significantly misrepresent temporal emission variability, whereas direct measurements provide more robust and reliable coal mine methane emissions estimates. We further show that applying emission factors to gross rather than net coal production reduces estimation errors and improves agreement with direct observations. Our findings demonstrate that continuous methane monitoring systems substantially improve mine-level emission inventories and highlight their importance for regulatory reporting, global methane databases, and the development of effective methane mitigation strategies.

Keywords:

coal mine methane, greenhouse gas inventory, methane monitoring, methane reporting, methane emission verification, emission factors

1. INTRODUCTION

Methane emissions during coal extraction are induced by pressure reduction within the coal seam during mining operations. Gas is released from newly formed fractures, desorbed

from fragmented coal, and liberated from surrounding strata disturbed by excavation (*Karacan et al. 2011; Szlqzak et al. 2019*). To maintain safe underground working conditions, methane is removed through mine ventilation systems and discharged to the atmosphere via ventilation shafts. Owing to strong dilution with air, methane concentrations in ventilation air are typically below 1 vol %, well outside the explosive range, and can be quantified using both laser absorption analyzers and conventional pellistor sensors (*Necki et al. 2026; Swolkien et al. 2022*). Methodologies for estimating greenhouse gas emissions, including coal mine methane (CMM), are defined by the Intergovernmental Panel on Climate Change (IPCC) (*IPCC 2006, 2019*). These guidelines classify estimation approaches into three Tiers characterized by increasing data specificity and decreasing uncertainty. Tier 1 applies global average emission factors to aggregate production data and requires minimal input information (*IPCC 2006, 2019*). Although straightforward to implement, this approach is associated with high uncertainty because methane content may vary by up to two orders of magnitude among coal seams and basins (*Dreger, Kedzior 2021; Swolkien et al. 2022*). Consequently, Tier 1 methodologies may substantially overestimate or underestimate methane emissions when applied at regional or national scales.

Tier 2 methodologies rely on country- or basin-specific emission factors derived from coal seam gas characteristics and production data (*Borchardt et al. 2025*). These approaches incorporate regional geological variability and mine-specific conditions, enabling more refined emission estimates. However, emissions are still estimated indirectly using production-based emission factors, which may be reported using either net or gross coal production values.

Tier 3 methodologies are potentially the most accurate because they rely on direct in-mine measurements from ventilation systems and methane drainage stations. However, the reliability of Tier 3 estimates strongly depends on measurement quality, temporal resolution, and sampling frequency. In the United States, methane measurements are commonly based on quarterly sampling, whereas Australian regulations allow both periodic and continuous monitoring approaches. For surface mining, Tier 3 methodologies are generally unavailable, and estimates remain dependent on Tier 2 approaches.¹² Although the IPCC currently allows the Australian “Method 2” gas distribution modeling framework to be classified as Tier 3 for surface mining, recent studies have questioned this classification because of poor agreement with top-down atmospheric observations (*Borchardt et al. 2025*). Currently, Tier 1 methodologies are still widely used in countries such as Indonesia and Brazil, whereas Tier 2 approaches dominate in

South Africa and Russia (*EMBER 2024; UNECE 2021*). Tier 3 approaches are less frequently used for national reporting but are increasingly applied in scientific studies, validation exercises, and operational analyses (*PNIR 2025; UNECE 2021*).

The Upper Silesian Coal Basin (USCB) in Poland is both the most productive and the most methane-intensive hard coal mining regions in Europe. Methane content within the basin varies substantially because of differences in mining depth, structural deformation, faults, and fracture systems (*Dreger, Kedzior 2021; Swolkien et al. 2022*). Coal seams are strongly inclined, producing large depth variations even within individual mining areas. Because methane content increases with depth, deeper southern mining districts are characterized by relatively elevated methane emissions. Additionally, methane-rich seams require extensive methane drainage to maintain safe mining conditions. The efficiency of methane capture and utilization therefore directly affects total atmospheric methane emissions and introduces additional complexity into production-based emission factor methodologies.

Under the new European Union Methane Regulation (*EU 2024/1787*), operators of underground coal mines are required to improve methane monitoring and reporting accuracy using best available techniques. Although Tier 2 approaches currently satisfy minimum reporting requirements, direct source-level measurements are strongly encouraged whenever technically feasible. Poland, as a Party to the UNFCCC and a member of the European Union, is additionally obligated to report fugitive methane emissions annually, with underground coal mining representing the dominant source within the energy sector (*PNIR 2025*).

Poland is currently the only European Union country with active hard coal mining, making the USCB an important natural laboratory for methane emission studies. Previous field campaigns conducted in the basin, including Methane-To-Go Poland and CoMet, demonstrated the suitability of the region for quantifying methane emissions from ventilation shafts and drainage systems and for evaluating methane inventory methodologies (*Necki et al. 2026; Förster et al. 2025; Swolkien et al. 2022; Swolkien 2020; Andersen et al. 2023; Luther et al. 2022, 2019; Fiehn et al. 2023; Krautwurst et al. 2021*)

In this study, we compare methane emission estimates derived from monthly and annually averaged emission factors and production-based methodologies with direct in-mine measurements from four underground coal mines in the USCB for 2024. The analysis focuses exclusively on operational methane emissions from ventilation shafts and methane drainage systems and does not include post-mining emissions or emissions associated with coal waste

processing. The results have direct implications for greenhouse gas inventory development, implementation of methane MRV (monitoring, reporting and verification) systems under Regulation (EU) 2024/1787, and reconciliation of bottom-up and top-down methane emission estimates. To our knowledge, this study presents the first temporally resolved comparison between Tier 2 emission factor methodologies and Tier 3 direct measurements for underground coal mines using high-resolution operational datasets.

2. MATERIALS AND METHODS

2.1. Overview of emissions from Upper Silesian Coal Basin (2024)

The USCB in Poland is the most industrialized hard coal mining area in the European Union and 95% of active Polish hard coal mines are located within this region. The total area of the USCB is 5,600 km², of which 3,049 km² contains documented deposits that account for 80% of Poland's hard coal resources (*PIG-PIB 2024*). In 2024, 19 hard coal mines working on 28 mining fronts in USCB released 722.1 million m³ of methane, of which 530.6 million m³ (355.5 kt) was emitted into the atmosphere (*WUG 2025*). According to the IPCC guidelines, in Poland (*PNIR 2025; Karbownik et al. 2024; Patyńska 2014*) the Tier 1 method is used to estimate emissions originating from surface mines, closed mines, and post-mining activities according to (1):

$$Emission (Gg CH_4) = EF (m^3 CH_4/tonne) \cdot Coal output (tonnes) \cdot Conversion Factor (Gg/10^6 m^3) \quad (1)$$

The Conversion Factor is taken as 0.67 Gg/10⁶ m³, representing gas density at 20°C and 1 atm pressure. EF in Tier 1 is selected using the IPCC guidelines (*IPCC 2019*).

For actively operating underground mines, a Tier 3 method is applied (*PNIR 2025; Patyńska 2014*). In Poland, the institution obligated to report yearly methane emissions is KOBiZE (National Centre for Emissions Management, Institute of Environmental Protection, National Research Institute) following national guidelines that adapt IPCC recommendations to the specific geological conditions and availability of direct measurements (*PNIR 2025; Kwarciański 2005; Patyńska 2014*). KOBiZE relies on yearly atmospheric emissions data obtained from the State Mining Authority (WUG), that oversees national mining operations. Each mine operator is obliged to report the total amount of methane released across the year, which includes methane captured by the drainage system (E_d in Table 1) and methane released through

ventilation system (E_{VAM} in Table 1). Data on utilized methane quantities (E_u in Table 1), the amount that has been combusted in gas engines, used for mine purposes, or sold, are provided in WUG reports collectively for the entire region. Table 1 shows the methane emissions data parameters from 2020 to 2024 (*WUG 2025*). Ultimately, methane emissions are reported to the UNFCCC by KOBiZE as total atmospheric emissions (E_{atm} in Table 1). In accordance with UNFCCC reporting requirements, KOBiZE also calculates the AEF index, expressed as tonnes of methane per kilotonne of coal. An emission factor approach is now used to assess compliance with EU Regulation 2024/1787.

Table 1

Development of total methane emissions, ventilation air methane, amount and efficiency of methane drainage and coal production in hard coal mines for the years 2020 to 2024 (*WUG 2025; netTG.pl*)

WUG data for coal production and methane emission for years:	2020	2021	2022	2023	2024
E_{VAM} – Ventilation Air Methane, mln m ³ CH ₄ /year	517	474	475	469	446
E_d – Drained methane, mln m ³ CH ₄ /year	303	341	303	283	276
E_u – Amount of utilized methane, mln m ³ CH ₄ /year	188	214	206	201	191
E_{atm} – Total atmospheric emission, mln m ³ CH ₄ /year	632	601	573	551	531
Net coal output, mln t	54.4	55.0	52.8	47.5	43.7
Net coal output from methane -prone deposits, mln t	44.06	44.55	41.60	38.62	36.90
Annual averaged methane emission factor (AEF), t/kt	7.78	7.32	7.27	7.77	8.14
Annual averaged methane emission factor (AEF) based on coal output of methane-prone deposits, t/kt	9.61	9.04	9.23	9.56	9.63

Since August 2024, operators of active underground coal mines have been required under EU Regulation (EU) 2024/1787 to implement measurement, reporting, and verification (MRV) systems using best available techniques, which may include IPCC Tier 2 methods where appropriate for emission factors. This regulation also envisages the progressive implementation of direct measurement-based monitoring approaches by 2027. Methane emission reports are also collected by State Mining Authority (WUG).

2.2. Deriving Tier-3 emissions estimates

The in-mine empirical approach to estimate methane emissions from coal mines is established by summing the airflow measurements from all ventilation routes connected to a given ventilation shaft and multiplying these with methane concentrations recorded in the shaft's ventilation channels by pellistor-based sensors. Because methane levels in ventilation airflow are continuously monitored to ensure safe underground conditions, thus pellistor measurements and data have been shown to reliably reflect actual operating conditions (Swolkien 2020; Swolkien et al. 2022; Su et al. 2005). High-accuracy methane sensors are not mandatory for ventilation shafts. Methane monitoring often relies on pellistor sensors, in addition mine operators routinely perform monthly sampling. Ventilation air methane (VAM) concentrations are verified using gas chromatography (GC). Methane drainage stations, however, are equipped with advanced measurement systems that continuously record methane concentration and flow rate, thus providing highly accurate and precise data.

The emission data delivered from given mines are converted to standard thermodynamic conditions, i.e., 20°C and 1 atm, according to the general formula (2) (Patyńska 2014):

$$E_{(N)} = E \cdot 293 / (273 + t_p) \quad (2)$$

where $E_{(N)}$ corresponds to the emission converted to standard conditions – ventilation or drainage system accordingly, E corresponds to the emission from the ventilation (E_{VAM}) or drainage system (E_d), and t_p represents the gas temperature in the ventilation shaft or drainage pipeline, respectively. The final methane emission is calculated collectively as (3):

$$E_{atm} = E_{VAM} + (E_d - E_u), \text{mln m}^3/\text{year} \quad (3)$$

where:

E_{atm} – Total atmospheric emission, mln m³/year

E_{VAM} – Ventilation air methane, mln m³/year

E_d – Amount of drained methane, mln m³/year

E_u – Amount of utilized methane, mln m³/year

Methane emission balances are conducted by mines on a monthly basis; however, reporting to WUG is performed annually.

2.3. Deriving Tier-2 emissions estimates

In Poland, methane emissions from underground coal mining are estimated using Tier 3 methodology based on in-situ measurements; therefore, the averaged emission factors (AEF) developed for the national mining sector are considered as high quality data (PNIR 2025). However, although these factors incorporate in-mine measurement data, they ultimately rely on net coal production and the overall fraction of fugitive methane that is drained and utilized (Table 1). This approach to calculating the AEF may introduce either positive or negative bias, depending on methane management practices at a given mine. Consequently, applying an emission factor derived in this way to estimate methane emissions at individual mines under the Tier 2 methodology may result in relatively high emissions particularly for (low gas) coal mines located in the northern part of the USCB.

Figure 1 provides a schematic overview of the procedure developed specifically for this study to estimate mine-level atmospheric methane emissions using a Tier 2 approach. Because coal production data for individual mines are generally not publicly available in Poland, annual atmospheric methane emissions reported by WUG (E_{atm} in Table 1) and regionally aggregated coal output statistics (Table 1) were used to derive an average emission factor (AEF). This AEF (8.14 t CH₄ kt⁻¹ for 2024) was subsequently applied to mine-specific production data obtained directly from mine operators to estimate atmospheric methane emissions for individual mines (left side of Fig. 1). These estimates were then compared with independent Tier 3 emission values derived from direct in-mine measurements (right side of Fig. 1).

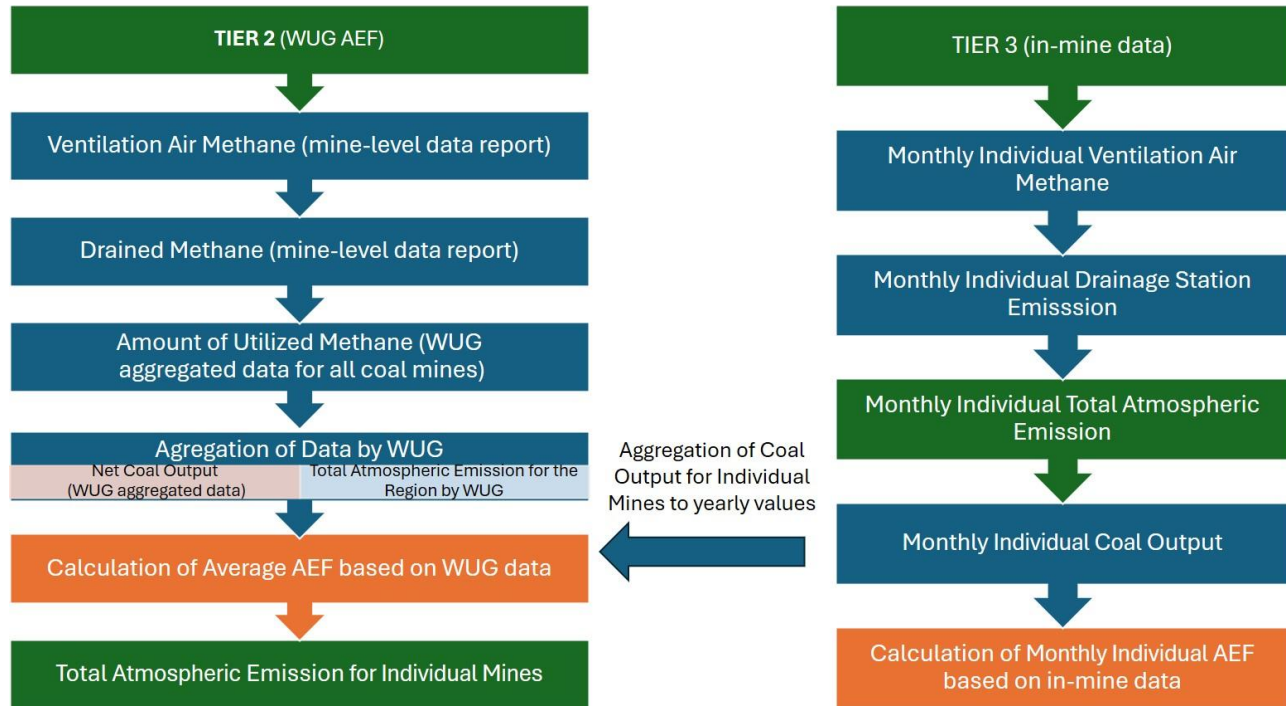


Fig. 1 Schematic of the data used in this paper

2.4. Tier-2 vs Tier-3

Table 2 presents a summary of key data related to both (Tier 2 and Tier 3) methodologies for measuring and estimating methane emissions in Polish underground coal mining. It outlines and compares the operating principles, data requirements, advantages, and limitations of applied methods.

Table 2 Summary of key data related to both methodologies for measuring methane emissions

Method	Principle	Typical Use	Data required	Strengths	Limitation
Tier 2 Emission Factor (EF) Production Bottom-Up approach	Estimates emissions by multiplying coal output by standardized national or source-specific empirical averaged methane emission factors ($\text{m}^3 \text{CH}_4/\text{t coal}$)	National/Regional inventories in countries lacking direct measurement infrastructure	- Annual total net coal output (tonnes) - Standardized, averaged methane emission factors ($\text{m}^3 \text{CH}_4/\text{t coal}$)	- Simplicity and scalability - Useful for regions lacking direct measurement infrastructure	- May not capture mine-specific variability - Sensitive to outdated values or non-representative EF values - Problem with net/gross production reporting

Tier 3. In-mine data approach	Uses direct measurements from VAM, drainage system (amount of drained methane and amount of utilized methane) and operational records to calculate actual methane emissions.	Detailed research, UNFCCC Greenhouse Gas Inventory Data, EU Regulation Reporting	• VAM sensor readings (methane concentration, air flow) • Drainage system methane volumes • Operational logs (coal output per coal mine)	• Higher accuracy and mine-specific granularity • Captures short term temporal and operational variability	• Requires extensive sensor networks and data management • Higher operational costs
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Overall, an emission factor-based methodology, while simple and scalable, cannot capture the variability that exists within and between individual mines (*Necki et al. 2026*). With yearly averaged values of methane emissions there are several inherent limitations:

1. Using the total amount of methane utilized for calculations.

Each mine is characterized by various levels of methane capture and utilization, which means that adopting a single value for the entire region may overestimate or underestimate actual emissions from a specific mine.

2. Simultaneous mining of seams with different methane contents.

Mining operations can be carried out on multiple coal seams simultaneously, each with distinct methane contents. The relative contribution of gas released from coal mined at different seams to total production can change over time, making averaged methane emission highly uncertain.

3. Using net production data instead of gross production in calculations.

This approach is not necessarily justified by the geological nature of coal seams and the extraction method. Since the extracted material contains both coal and waste rock, and mining may disturb bedrock and leads methane release, using gross production as the denominator in calculating *EF* can be more appropriate. Although the balance between methane content of waste rock should be taken into consideration.

Considering the arguments above, Tier 2 methods may not adequately capture mine-level variability and can introduce substantial uncertainty when applied to heterogeneous mining systems. By contrast, an empirical approach that relies on directly measuring emissions for

individual coal mines is preferable. As stated in section 2.2 methane emission estimates are performed using monthly sampling, and ventilation air methane (VAM) concentrations are determined using gas chromatography (GC). It is worth noting that discrete monthly sampling may not adequately capture the temporal variability of methane concentrations in ventilation shafts (Swolkien 2020; Swolkien et al. 2022) related to weekly or daily changes in mining operations and production rates. Distinct temporal patterns in ventilation air methane concentrations become apparent only when measurements are recorded at high frequency using accurate analysers, such as tunable diode laser absorption spectroscopy (TDLAS), which can resolve rapidly changing emission dynamics (Necki et al. 2026).

Methane release at drainage stations, on the other hand, is quantified using continuous records of methane concentration and flow rates, thus providing high resolution and quality data (Dyczko 2023). There is, therefore, a temporal and quality mismatch between monthly GC-based VAM measurements and the highly resolved methane data obtained from drainage stations. Partial reconciliation is possible through methane tele-transmission safety monitoring systems, which record data at one-second resolution and are typically averaged to hourly values, thereby providing a valuable resource for characterizing changes in VAM. These safety systems operate at numerous locations, including return ventilation shafts, and can serve as an accurate source of emission data (Dyczko 2023). However, operators rarely employ these datasets for estimating atmospheric methane emissions. A methodology for integrating such high-frequency data, through systematic calibration and standardized data processing, into routine emission reporting has already been proposed and is expected to outperform the current approach (Necki et al. 2026). In this context, limitations associated with measurement uncertainty and data quality in safety sensor networks may be reduced through standardized calibration of commonly used pellistor sensors and regular validation against high-precision TDLAS instrumentation. Direct measurements provide the most reliable approach for characterizing temporal variability of emissions from individual point sources such as ventilation shafts and methane drainage stations. Moreover, combining these emission data with precise production figures from coal mines operators, enables more accurate local-level analyses and reduces emission estimate uncertainty.

3. RESULTS AND DISCUSSIONS

3.1. Comparative annual analysis

A common challenge in reconciling inventory-based emission estimates with atmospheric observations is the temporal mismatch between annual average EF-based data and limited point-in-time atmospheric measurements (*Borchart et al. 2025*). By contrast, well-calibrated in-mine monitoring systems can provide more than 500,000 data points per year, offering comprehensive temporal coverage. Such high-resolution datasets enable a detailed characterization of the temporal variability of emissions from ventilation systems. At present, however, most top-down measurement campaigns still rely on annual average emission reports when comparing indirect atmospheric observations with coal-mine emission inventories. This comparison is inherently limited by the absence of similar temporally resolved coal-production data. Although run-of-mine and sales production volumes are monitored with high accuracy, these datasets are considered commercially sensitive and are therefore usually not publicly available. When production data are accurate, the dominant source of uncertainty in emission estimates arises from the applicability and representativeness of the emission factors. This raises the issue of the variability of methane emission data used to derive emission factors as mine development potentially encounters coal with different characteristics. Characterizing temporal variability in methane emissions requires sufficiently large and temporally resolved datasets. For the region considered in this study an indication of the variability within a year, and the trend from one year to the next, provides context needed for the analysis of past emissions. Figure 2 illustrates historical emission estimates from the National Inventory Reports and the State Mining Authority spanning the period 1988–2023 (*PNIR 2025*).

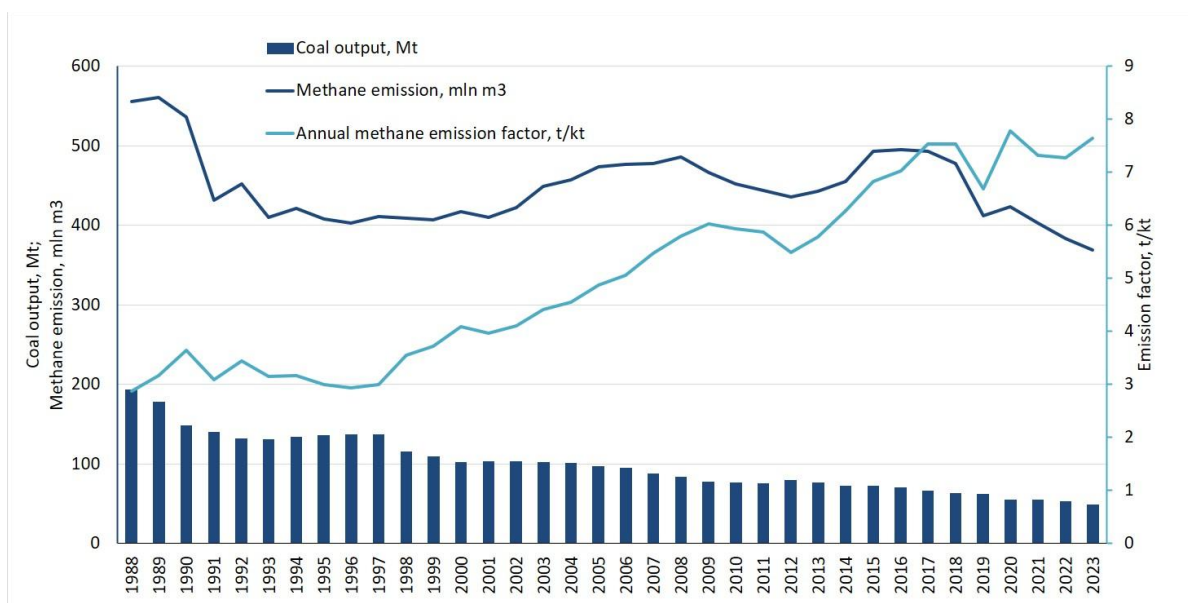


Fig. 2 Historical trends in methane emissions, coal output, and annual emission factors in Poland between 1988 and 2023 (*PNIR 2025*)

Figure 2 reflects a general long-term decline in coal output, from a maximum of 193 Mt in 1988 to a minimum of 48 Mt in 2023, with some periods of relative stability. This nearly fourfold reduction in output is accompanied by a corresponding decrease in the number of active coal mines, driven largely by economic factors in Poland.

Methane emissions exhibit a more complex temporal pattern. In the initial period (1988–1993), emissions decline rapidly from over 550 million m³ to approximately 420 million m³, largely reflecting the reduction in coal output. This is followed by a relatively stable period between 1993 and 2000. From around 2000 onwards, they increase gradually, reaching nearly 500 million m³ by 2015 despite declining coal output. Between 2015 and 2019, emissions show increased variability, followed by a clear decline toward approximately 370 million m³ in 2023.

The annual emission factor (AEF), derived as the ratio of methane emissions to net coal production, represents an inferred measure of emission intensity. While AEF values remained relatively stable until around 1997, they have increased consistently thereafter, more than doubling from approximately 3.5 t/kt to 7.6 t/kt by 2023. Importantly, in the final years of the study period, AEF remains elevated despite declining total emissions. This is primarily because coal production stabilized at a relatively low level, amplifying the effect of emission intensity on the calculated emission factor.

This trend is also likely linked to geological and operational factors. Deeper coal seams generally show higher methane contents, and in Poland, average mining depths range from approximately 800 to 900 m, increasing at a rate of about 7–8 m per year (*Szłqzak, Swolkieñ 2023*). While depth changes at individual mines may not substantially alter their specific AEF values, the aggregated AEF is strongly influenced by mines operating in deeper, more methane-rich seams.

Overall, these results demonstrate that methane emissions do not scale directly with coal output. In particular, in the most recent period, the reduction in emissions is driven mainly by declining production, while the persistently high AEF reflects elevated emission intensities under low-output conditions.

While data for 2024 are not yet available (current PNIR presents data for 2023), methane emissions for that year are expected to remain comparable, as no mine closures have occurred during this period. The parameters shown in Figure 2 represent regional averages, whereas their applicability to the four mines examined in this study is evaluated below.

Robust method validation requires that the regional parameters (Figure 2) are compared with analogous parameters derived from in-mine measurements. Table 3 presents coal- output and methane-emissions data for each of the four mines under observation, based on WUG statistics for 2024 (*WUG 2025*) and in-mine datasets for 2024. Annual estimates of emissions from ventilation shafts, drainage systems, atmospheric emissions, and coal-output values for individual mines are provided in terms of both gross production (including waste rock) and net coal production.

Table 3.
Development of total methane emissions, ventilation air methane, emission from drainage station in analyzed hard coal mines in 2024 based on WUG and in-mine data (*WUG 2025*) and direct in-mine measurements

Coal mine	Source	VAM, mln m ³	Emission from drainage station mln m ³ /year	Total atmospheric emission, mln m ³ /year	Coal output, kt/year	
					net	gross
Coal mine I	WUG	11.02	Not available	Not available	Not available	
	In-mine data	11.02	0.611	11.63	922.70	Not available
Coal mine II	WUG	14.06	Not available	Not available	Not available	
	In-mine data	14.06	3.20	17.26	1646.00	3265.19

Coal mine III	WUG	50.68	Not available	Not available	Not available	
	In-mine data	43.04	0.90	43.95	1951.75	3420.96
Coal mine IV	WUG	53.54	Not available	Not available	Not available	
	In-mine data	54.59	0.90	55.50	2100.09	6132.61

A comparison of ventilation air methane (VAM) emissions for the analysed mines (Table 3) shows that, for three of the four mines, values reported by WUG are consistent with direct in-mine measurements. However, WUG datasets do not provide mine-level information on drainage station emissions or total atmospheric methane emissions; instead, these parameters are reported as regional aggregates (E_{atm} in Table 1). Consequently, coal production data are critical for estimating mine-level emissions using the production-based Tier 2 methodology and the 2024 WUG-derived annual emission factor (AEF; 8.14 t/kt).

Table 4 summarizes AEF values calculated from direct emission measurements and mine-specific production data for the four analysed mines. These values are further compared with emissions estimated using the WUG-derived AEF together with mine-specific net and gross coal output data.

Table 4. Comparison of annual averaged emission factors (AEFs) and methane emissions derived from WUG-based Tier 2 estimates and direct in-mine Tier 3 measurements using net and gross coal output data

Name			Coal mine I	Coal mine II	Coal mine III	Coal mine IV
National EF and Production BU approach* Tier 2	AEF, t/kt		8.14			
	Emission, kt		7.51	13.40	15.89	17.09
In-mine data approach Tier 3	AEF, t/kt	net	8.44	7.03	15.09	17.71
		gross	-	3.54	8.61	6.06
	In-mine emission, kt		7.79	11.90	30.32	38.29
Relative difference, %			3.6	12.6	47.6	55.4
	EF, t/kt		16.75			

Global EF and production BU approach** Tier 1	Emission, kt	15.50	27.57	32.7	35.20
UNEP-IMEO Satellite, top-down approach	Top-down Emission, kt	-	74.05 ± 5%		32.80 ± 9%

* Data calculated based on AEF from Table 1 and in-mine net output. **Data calculated based on IPCC Guidelines Tier-01 default emission factor for underground mining with depth >400m and in-mine net output from Table 1.

Emission estimates derived from the WUG emission factor showed good agreement only for Coal Mine I, where the relative difference between Tier 2 and Tier 3 emissions was 3.6%. In this case, the mine-specific AEF calculated from direct measurements closely matched the WUG-derived coefficient. However, discrepancies increased substantially for the remaining mines, reaching 12.6% for Coal Mine II, 47.6% for Mine III, and 55.4% for Mine IV.

The WUG-derived AEF values presented in Table 4 are based on regional production statistics and net coal output. Although these coefficients originate from data reported by individual mines, their application at the mine level introduces substantial uncertainty because they implicitly assume stable production shares between methane-rich and low-emission mines across the basin. This assumption is rarely satisfied in practice. Consequently, generalized regional emission factors may systematically overestimate emissions from lower-emission mines while underestimating emissions from methane-intensive operations.

Table 4 additionally demonstrates the strong sensitivity of AEF values to denominator selection. When gross extracted material is used instead of net coal output, calculated AEF values decrease by factors of 1.98, 1.75, and 2.92 for mines II, III, and IV, respectively. These results indicate that net coal output may artificially amplify production-normalized methane intensity indicators because methane release is more directly associated with total rock mass disturbance and ventilation requirements than with saleable coal production alone.

In-mine Tier 3 estimates were further compared with bottom-up estimates derived using the IPCC Tier 1 default emission factor for underground mines deeper than 400 m and with top-down estimates derived from UNEP IMEO satellite observations (UNEP IMEO 2026). Application of the IPCC default factor (16.75 t/kt) produced moderate agreement for methane-rich mines III and IV, but substantially overestimated emissions from mines I and II. This

finding further illustrates the limitations of generalized emission factors for representing heterogeneous mining conditions.

Comparison with satellite-derived estimates revealed mixed agreement with direct in-mine measurements. Satellite estimates were derived by identifying individual methane-emitting sources within each mine boundary, assigning detected plumes to these sources, and extrapolating the resulting instantaneous observations to annual emissions using a statistical framework that accounts for both plume detections and non-detections (*UNEP IMEO 2026*). For mines II and III combined, 17 plume quantifications and 69 non-detections yielded an annual estimate of $74.05 \pm 5\%$ kt, substantially higher than the corresponding Tier 3 estimate of 42.22 kt. In contrast, for mine IV, where 25 plume quantifications and only 7 non-detections were available, the satellite-derived estimate ($32.80 \pm 9\%$ kt) was moderately lower than the direct in-mine measurement (38.29 kt). The differing levels of agreement likely reflect uncertainties associated with extrapolating episodic satellite observations to annual emissions. Estimates become increasingly sensitive to the extrapolation framework when observational coverage is sparse, as illustrated by the much larger number of non-detections for mines II and III than for mine IV. In addition, this framework assumes a minimum baseline emission rate for each identified sub-source, although not all sub-sources may emit continuously throughout the year. Source attribution also remains challenging where multiple emission points are closely spaced, as plumes observed under complex wind conditions may represent emissions from more than one source. Consequently, these results should be viewed as an initial reconciliation between bottom-up and top-down estimates. Future improvements in any annualization framework will require incorporation of mine operational information (e.g., ventilation schedules and source persistence) along with improved representation of atmospheric transport and complex wind fields. Such developments, together with increasing repeated satellite observations, will strengthen the reconciliation between top-down and in-mine methane estimates. These findings illustrate that the current use of satellite platforms is restricted as a verification tool that is under development.

3.2. Comparative monthly analysis

Annual methane emission estimates derived from emission factors (EFs) and production data are inherently unable to capture short-term (i.e., monthly) variability in methane release

from underground coal mines. Methane emissions from ventilation shafts and drainage systems are influenced by mine-specific geological factors, including seam depth, methane content, and geological structure, as well as operational disturbances and ventilation requirements that may vary independently of coal production. Comparison of direct in-mine measurements (Tier 3) with EF-based estimates (Tier 2) therefore provides an opportunity to evaluate the reliability of the production-based methodologies currently applied in national greenhouse gas reporting frameworks. For this purpose, we used operators supplied monthly data on methane emissions together with net and gross coal production for 2024.

Figure 3 compares monthly methane emissions derived from direct in-mine measurements with estimates calculated using the WUG-derived annual emission factor (AEF; 8.14 t/kt) and net coal output.

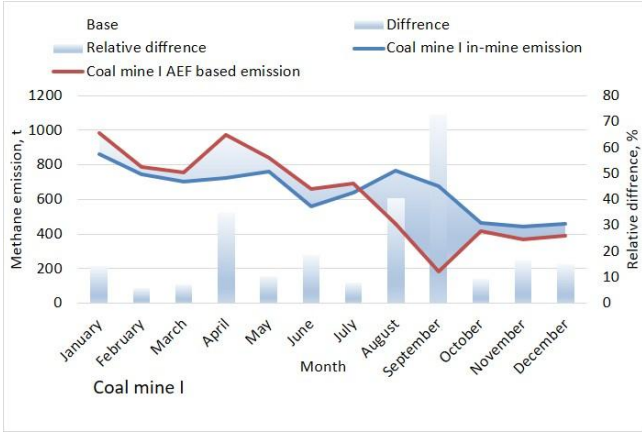


Fig. 3a

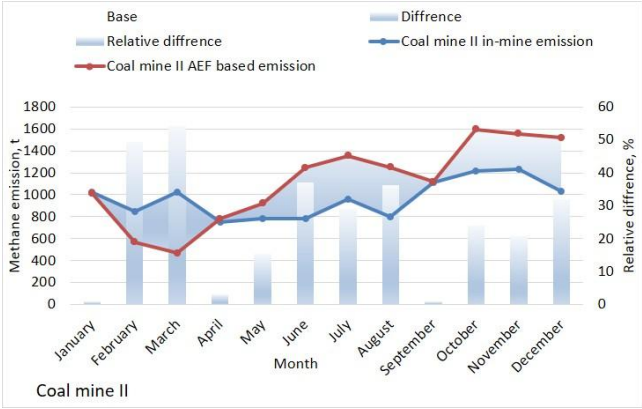


Fig. 3b

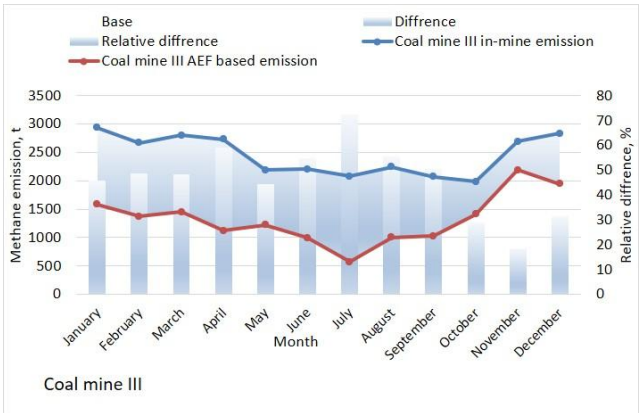


Fig. 3c

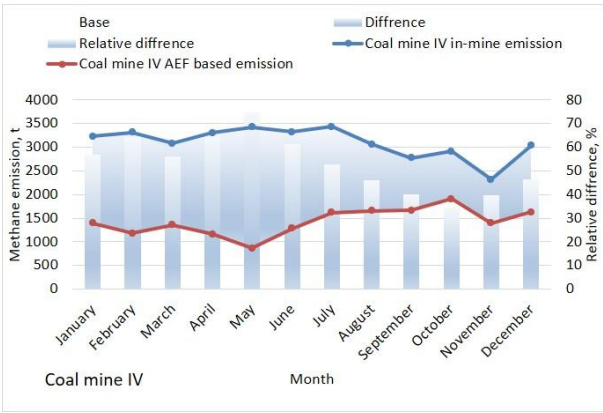


Fig. 3d

Fig. 3 Comparison between methane emissions estimated using the WUG-derived annual emission factor (AEF) and direct in-mine measurements for four underground coal mines in 2024: (a) mine I, (b) mine II, (c) mine III, and (d) mine IV. Blue lines represent measured in-mine emissions, red lines represent AEF-based estimates, bars indicate relative differences and the shaded area differences in results

The data presented in Figure 3 (individual panels for each mine) demonstrate substantial discrepancies between emission estimates derived from the WUG AEF (8.14 t/kt) and directly measured in-mine emission estimates. These discrepancies are neither uniform across mines nor temporally stable throughout 2024, indicating structural limitations of the EF-based approach at a monthly time resolution. For mines I and II, relative differences fluctuate in both directions. EF-based estimates exceed in-mine emissions by approximately 21% on average in Mine I and 25% in Mine II. However, the sign of the deviation alternates throughout the year. In Mine I, EF-based estimates tend to be higher in the first seven months of the year and lower in the later months. The opposite pattern is observed in Mine II, where EF-based estimates are generally lower in the first three months and higher toward the end of the year. Monthly percentage deviation amplitudes were substantial in both mines, peaking in August–September for coal Mine I (up to 72%; Fig. 3a) and February–March for Coal Mine II (up to 54%; Fig. 3a).

This alternating behaviour indicates that discrepancies in mines I and II are largely production-driven rather than methane concentration-driven. Because the EF-based methodology scales directly with coal output, production variability can strongly influence calculated emissions independently of actual methane release. As a result, the EF approach introduces artificial variability that does not necessarily reflect actual emission dynamics. In contrast, mines III and IV exhibit a persistent and unidirectional discrepancy. For both of these highly methane-prone mines, emission factor-based estimates are consistently lower than in-mine measurements throughout the year. On average, in-mine emissions exceed AEF-based estimates by approximately 46% (Coal Mine III; Fig. 3c) to 53% (Coal Mine IV; Fig. 3d). The relative differences are more stable over time than in-mines I and II, indicating systematic underestimation rather than a variable seasonal behaviour. This persistent bias suggests that the generalized WUG-derived AEF does not adequately represent methane-rich mining conditions. Importantly, when month-to-month variability is considered independently of production fluctuations, the empirically measured in-mine emissions display greater temporal consistency than EF-based estimates across all four mines. This indicates that the observed instability in EF-derived emissions arises primarily from the mathematical structure of the production-based approach rather than from actual changes in methane emissions.

Overall, the mine-specific analysis clearly demonstrates that applying a single national annual emission factor to heterogeneous mining conditions results in both systematic bias (mines III and IV) and production-driven variability (mines I and II). These characteristics limit the

reliability of EF-based estimates for representing short-term emission dynamics and raise questions regarding their suitability for detailed performance assessment at the mine level.

The apparent agreement between annual emission estimates for mine I (Table 4) results primarily from the close agreement between the WUG-derived annual emission factor (8.14 t/kt), corresponding to a difference of only 3.6%. However, this annual convergence masks substantial intra-annual variability (Figure 4). Indeed, the monthly AEF values derived from in-mine data reveal pronounced fluctuations around the WUG reference. In Mine I, the coefficient remained relatively close to the WUG value between January and July, with moderate deviations. However, in August and September, the AEF increased sharply to 13.66 t/kt and 29.83 t/kt, respectively. The September value corresponds to approximately 3.7 times the WUG factor. These abrupt increases coincided with reduced output rather than a proportional increase in methane emissions, indicating strong denominator sensitivity. A similar output-driven effect was observed in-mine II. In February and March, the in-mine AEF rose markedly compared to adjacent months, while in January, April, and September it approximated the WUG-derived value. In several remaining months, the in-mine AEF fell below 8.14 t/kt. This alternating pattern confirms that monthly deviations are not governed solely by emission intensities but rather by output variability. By contrast, mines III and IV exhibit persistent structural divergence from the WUG reference factor. Throughout 2024, the in-mine AEF values for these mines ranged from 1.20 to 4.00 times the WUG-based coefficient. Unlike mines I and II, where temporary alignment occurred in selected months, mines III and IV did not demonstrate significant overlap with the estimates using national factor. The discrepancy is therefore systematic rather than episodic.

These results demonstrate that the application of a generalized WUG-derived AEF is only reliable when the mine-specific emission characteristics are comparable to the national average, as observed for Mine I. However, even under this scenario monthly emission estimates do not consistently scale. When the in-mine AEF exceeds the WUG value, emissions are structurally underestimated with the EF-based approach; conversely, when it falls below, emissions are largely overestimated. In methane-rich mines such as III and IV, the WUG-derived factor fails to represent actual emission intensities across the entire year. This persistent deviation reflects the geological conditions of these operations, which are among the most methane-rich in the entire USCB.

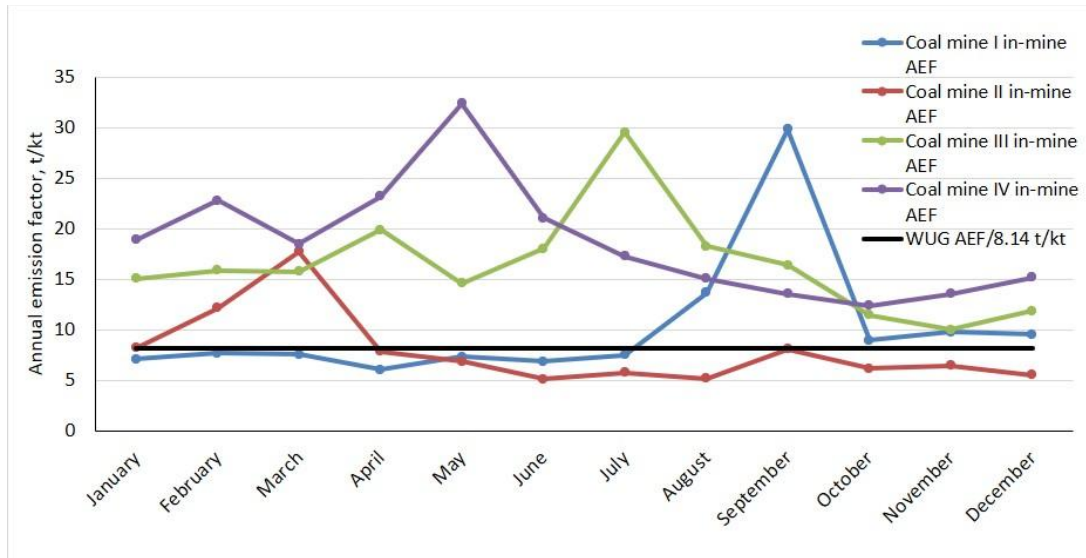


Fig. 4 Comparison of AEF values derived from WUG and direct in-mine data for 2024

The calculation of the WUG-derived AEF using total annual output from both methane-rich and low-emission mines further introduces even more bias. Applying this aggregated national coefficient to individual mines results in systematic underestimation of emissions from methane-rich operations and overestimation of emissions for mines with lower emission intensities, as demonstrated in Figures 3 and 4. However, considering that methane-rich mines release much more gas than methane-poor mines, these effects do not cancel each other out and cumulatively, for these four mines, this leads to lower methane emission. This difference arises from the heterogeneity of geological and operational conditions within the mining sector, which cannot be adequately represented by a single averaged emission factor.

3.3. Temporal variability in emission factor

To further illustrate the relationship between methane emissions, production volume, and annual averaged emission factor (AEF) values, Figures 5a-5d present monthly trends in methane emissions and AEFs as functions of net coal output for each analysed mine.

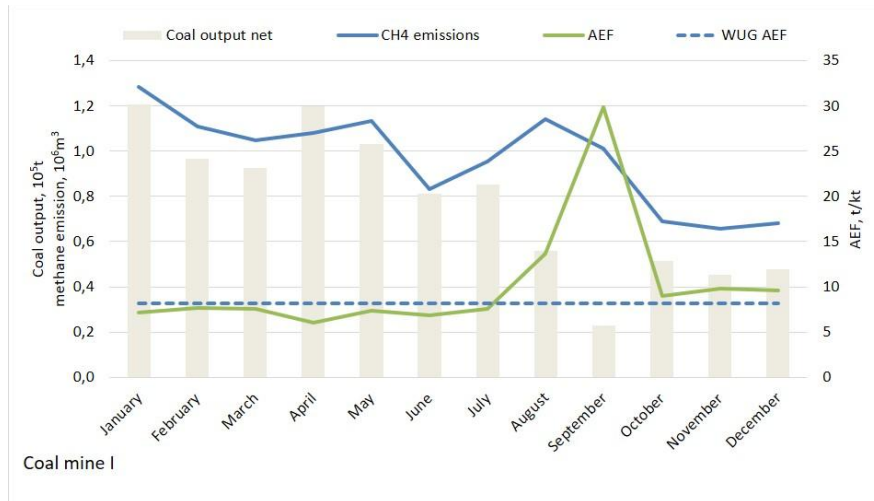


Fig. 5a

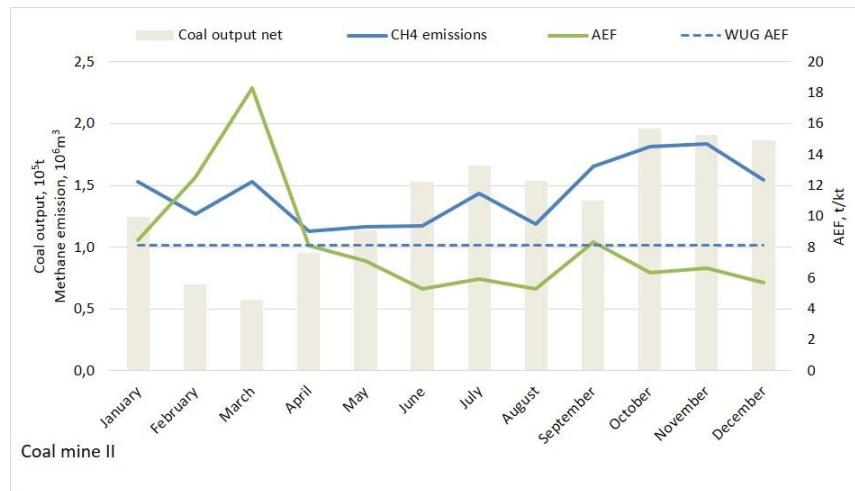


Fig. 5b

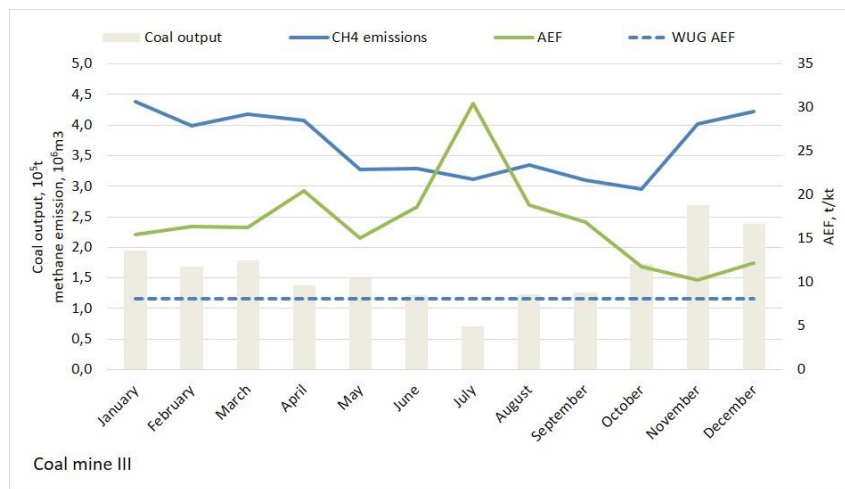


Fig. 5c

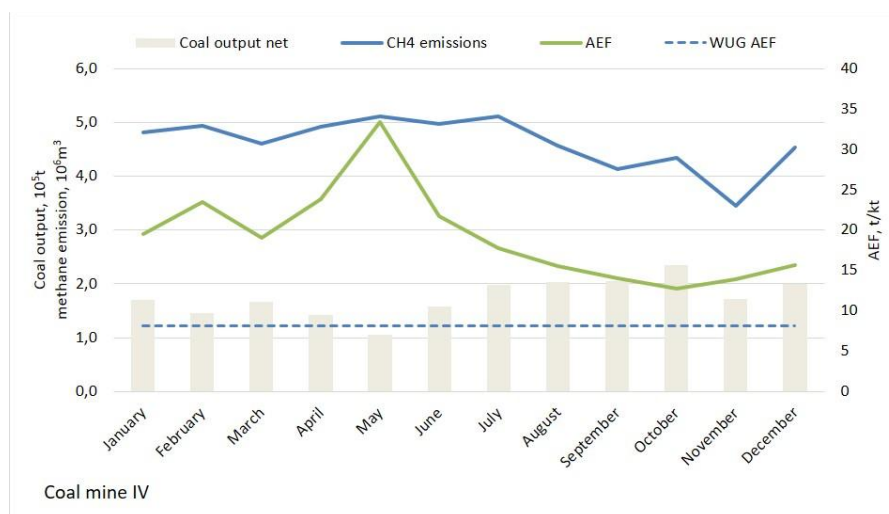


Fig. 5d

Fig. 5 Monthly methane emissions, net coal output, and annual averaged emission factor (AEF) values for: (a) mine I, (b) mine II, (c) mine III and (d) mine IV in 2024. The shaded line represents the WUG-derived AEF

Analysis of data (Figures 5a-5d) demonstrates that AEF variability is governed primarily by production dynamics rather than proportional changes in methane emissions. Because AEF is defined as emissions per unit of output, reductions in production amplify the coefficient regardless of methane release. For example, in Mine I (Fig. 5a), a substantial reduction in production during August and September, associated with a rock burst event, resulted in a sharp increase in AEF despite relatively stable methane emissions. The coefficient increased from 7.53 t/kt in July to 29.84 t/kt in September, representing nearly a fourfold increase within two months. Similarly, in Mine II (Fig. 5b), reduced production in March caused a pronounced increase in AEF, whereas the highest methane emissions recorded in November corresponded to substantially lower AEF values because of higher production volumes. Comparable production-driven effects were observed in mines III and IV (Figs. 5c and 5d), where months characterized by similar methane emissions produced markedly different AEF values depending on coal output.

Across all four mines, these relationships demonstrate that AEF responds more strongly to changes in production volume than to changes in methane emissions, showing again that AEF is a structurally denominator-sensitive indicator. This characteristic becomes particularly important when regionally averaged WUG-based AEF values are recalculated using only methane-prone coal mines. This substantially increases the resulting coefficients (Table 1) and

highlights the influence of aggregation and denominator selection on reported emission intensity values.

Given that AEF-based metrics are increasingly used within regulatory frameworks, including Regulation (EU) 2024/1787, denominator selection has implications extending beyond methodological consistency. The observed sensitivity to fluctuations in net coal production suggests that gross extracted material may provide a more representative basis for methane intensity calculations because methane release is more directly related to total rock mass disturbance and ventilation requirements than to the quantity of saleable coal alone.

3.4. Sensitivity to choice of coal output type

Because emission intensity indicators are inherently sensitive to the production metric used in their calculation, AEF values were recalculated using gross extracted material rather than net coal output (Fig.6s-6c). Comparing the two approaches (Fig. 7a-7c) allows assessment of the extent to which denominator selection influences the magnitude and temporal variability of methane intensity estimates at the mine level.

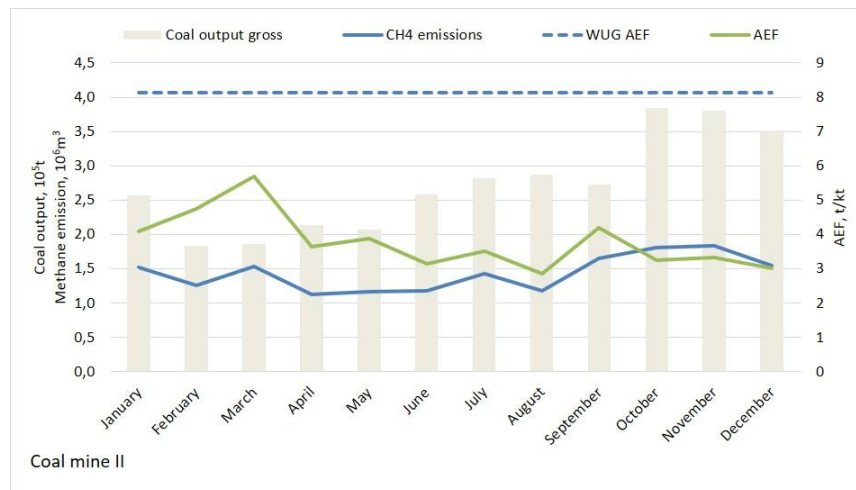


Fig. 6a

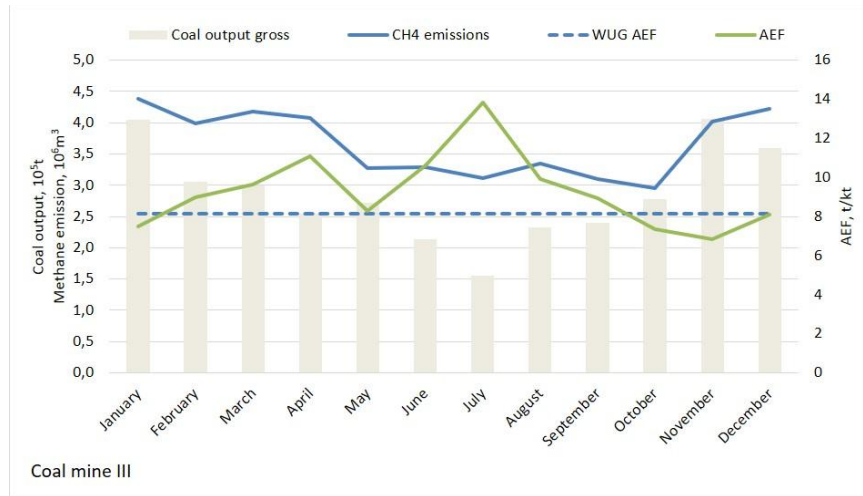


Fig. 6b

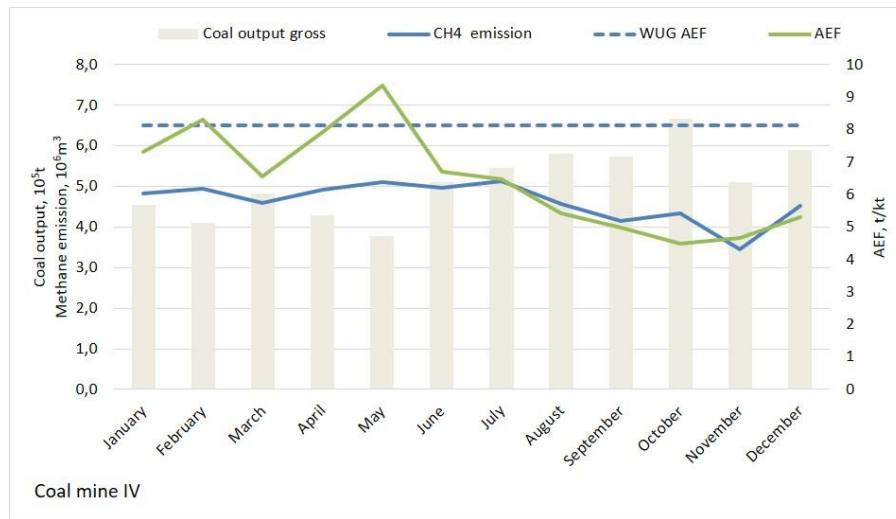


Fig. 6c

Fig. 6 Relationship between methane emissions, gross coal output, and AEF values for (a) mine II, (b) mine III, and (c) mine IV in 2024

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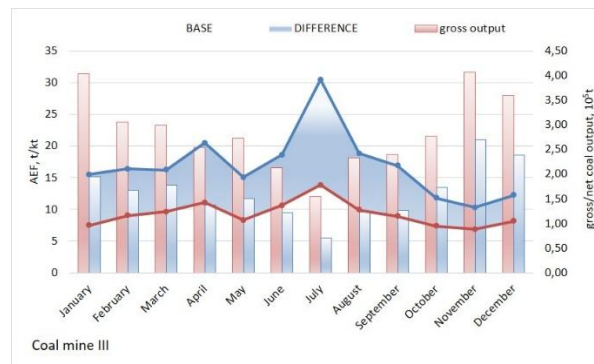
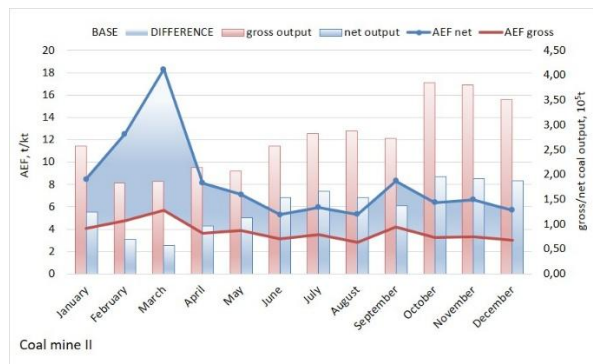


Fig. 7a

Fig. 7b

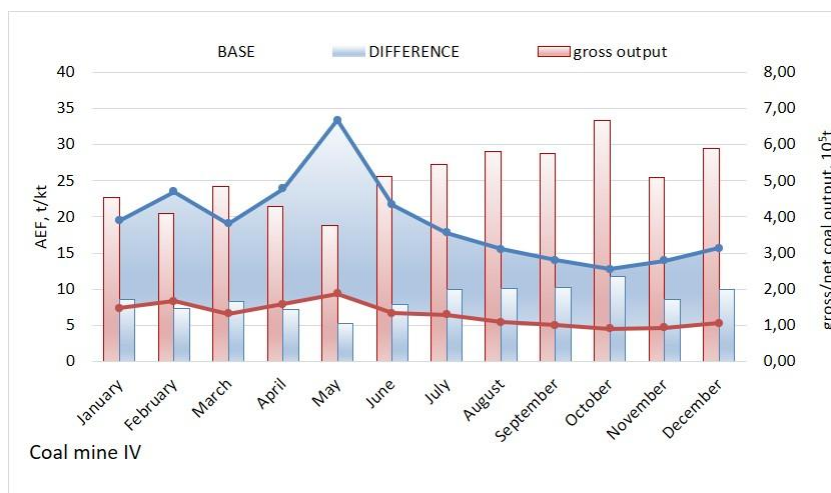


Fig. 7c

Fig. 7 Comparison between AEF values calculated using net and gross coal output for: (a) mine II, (b) mine III, and (c) mine IV in 2024. Shaded areas represent differences between the two approaches.

To assess the magnitude and consistency of this denominator effect under different geological and operational conditions, the results are discussed separately for each mine. Across all analysed mines, replacing net coal output with gross extracted material systematically reduced both the magnitude and temporal variability of AEF values. The reduction was particularly pronounced in methane-rich mines characterized by elevated waste-rock extraction and variable saleable coal yield.

In Mine II, the use of gross output reduced AEF values by approximately a factor of two and substantially attenuated short-term variability associated with temporary production declines. The previously observed contrast between March and November AEF values under the net-output formulation was therefore largely attributable to denominator sensitivity rather than to actual changes in methane emissions.

Similar behavior was observed in Mine III, where recalculation using gross output reduced the apparent variability of methane intensity indicators despite persistently elevated methane emissions. This effect was particularly evident during months characterized by comparable methane emissions but different saleable coal yields, indicating that a substantial portion of the apparent AEF variability originated from fluctuations in net production rather than from actual emission dynamics.

Mine IV exhibited the strongest denominator sensitivity. In selected months, net-output AEF values exceeded gross-output estimates by more than a factor of three. On an annual basis, the average AEF decreased approximately threefold when gross extracted material was used as the denominator. This result demonstrates that net-output formulations may substantially exaggerate methane intensity in-mines characterized by high waste-rock extraction and operational variability.

Overall, the results indicate that net coal output is not a neutral accounting denominator but a variable that can substantially influence methane intensity metrics. Replacing net coal production with gross extracted material systematically reduced AEF variability, decreased sensitivity to short-term fluctuations in saleable coal yield, and improved alignment with the physical processes governing methane release. Because methane emissions are more directly associated with rock mass disturbance, seam gas content, and ventilation requirements than with the quantity of marketable coal produced, the use of gross extracted material may provide a more robust basis for methane intensity assessment.

These findings have important implications for methane monitoring, reporting, and verification (MRV) frameworks, particularly in the context of Regulation (EU) 2024/1787. Methane intensity metrics that depend strongly on net coal production may be influenced by fluctuations in production levels that are unrelated to actual methane emissions or mitigation performance. Consequently, denominator selection should be carefully considered when developing emission benchmarks, evaluating mitigation measures, and comparing methane intensities across mining operations.

4. CONCLUSIONS

This study evaluated methodologies used to estimate methane emissions from underground coal mines by comparing Tier 2 emission factor (EF)-based approaches with direct in-mine measurements (Tier 3). The results demonstrate that although EF-based methodologies may provide reasonable estimates at aggregated annual scales, they often fail to accurately represent emissions at the level of individual mines. The magnitude and direction of these discrepancies are strongly site-specific and reflect geological heterogeneity, methane management practices, and operational conditions.

Our analysis further demonstrates that annual averaged emission factors (AEFs) are highly sensitive to production variability because they are intrinsically defined as production-normalized metrics. Consequently, fluctuations in coal output may strongly influence AEF values even when methane emissions remain relatively stable. In methane-rich mines, this denominator sensitivity leads to systematic underestimation of emissions under Tier 2 approaches and may artificially amplify emission intensity during periods of reduced production. The results additionally show that using net coal output further exaggerates this effect, whereas gross extracted material provides a more physically representative basis for characterizing methane release associated with rock mass disturbance and ventilation requirements.

These findings indicate that production-based emission factors should be applied cautiously for mine-level emission assessment, benchmarking, and mitigation planning. While national emission factors remain useful for regional inventories, they are insufficient for accurately resolving temporal and spatial variability in methane emissions from individual underground mines. In contrast, direct measurement approaches provide substantially more robust and transparent emission estimates and improve the comparability of methane inventories across mines and reporting frameworks.

The results also suggest that revisiting the methodological basis of AEF calculations could improve consistency between regulatory methane intensity metrics and the physical processes governing methane liberation. This issue is particularly relevant in the context of emerging methane regulations, including Regulation (EU) 2024/1787, which increasingly rely on emission intensity indicators for reporting and mitigation assessment.

Finally, the ongoing modernization of methane monitoring and tele-transmission systems in underground mines creates an opportunity to substantially improve greenhouse gas reporting frameworks. The integration of continuous monitoring systems with standardized measurement and reporting protocols would improve the robustness, temporal representativeness, and policy relevance of methane emission inventories while supporting more effective methane mitigation strategies.

Beyond the specific case of Polish coal mines, the results demonstrate the challenges associated with applying production-based emission factors in heterogeneous mining systems. As methane inventories increasingly support regulatory compliance, satellite verification, and

methane mitigation policies, improved integration of continuous monitoring data into inventory frameworks will become essential for robust MRV systems.

Author Contributions

J.S. conceptualized the study, analyzed the data, and prepared the original manuscript draft. J.N. contributed to methodology development and manuscript revision. R.F. and K.T. contributed to study design, data interpretation, and manuscript preparation and revision. All authors reviewed and approved the final manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Data Availability Statement: Operational mine datasets are available from the corresponding author upon reasonable request. Certain datasets are subject to confidentiality restrictions imposed by mine operators.

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