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ESTIMATION OF FUGITIVE EMISSIONS FROM OPEN CUT COAL MINING AND MEASUREABLE GAS CONTENT

Abouna Saghafi

ABSTRACT: To evaluate fugitive emissions from open cut coal mines, emission factor values of 3.2 m³/t and 1.2 m³/t have been used for the two main Australian coal-producing states of New South Wales and Queensland, respectively. CSIRO developed these values in the early 1990s. They were meant for use as average regional values (Tier 2 method), but were subsequently used for all mines, irrespective of the level of 'gassiness' of specific coal seams and strata. Over the past decade, a new method has been developed for Australian open cut mining that is specific to each mine site (Tier 3 method). The proposed method has been adopted by National Greenhouse and Energy Reporting and is the basis of Method 2 or 3 for calculation of emissions. The new method is based on an emission model, which considers the coal seams and sedimentary gas-bearing horizons (layers) as individual gas reservoir units. These units release part or all of their gas during mining. The main data required are *in situ* gas content, gas composition and thickness of the gas-bearing horizons within the column of strata above and below the mine base. In this method, drilling can be reduced by partitioning the mine site into 'gas zones' in which similar patterns of gas distribution are expected. Two to three core drillings are required to characterise a gas zone and to provide the main input of the model. Routine geophysical log data can also provide the thickness of gas-bearing layers. Because of the limitations of the standard gas content measuring method, different commercial laboratories claim various limits of detection (i.e. measurability). However, in view of the very different global warming potential values of coal seam gas components, different limits of measurability can lead to significant differences in the estimation of fugitive emissions.

INTRODUCTION

In the early 1990s, a method of estimating fugitive gas emissions from open cut coal mines based on direct measurement of gas plumes emitted from 17 open cut coal mines in the Sydney and Bowen Basins was developed (Saghafi and Williams, 1992; Williams and Saghafi, 1993; Williams, *et al.*, 1996). Emissions from these mines were determined using an air pollution technique, involving the measurement of wind speed and gas concentration above the ground in the proximity of emissions sources (one or a group of coal mines). Subsequently, an average emission factor (*EF*) of 1.2 m³/t methane (CH₄) was established (equivalent to 0.017 t of carbon dioxide (CO₂) per tonne of raw coal) for open cuts of the Bowen Basin and an *EF* value of 3.2 m³/t (or 0.045 t of CO₂ per tonne of raw coal) for the open cut mines of the Hunter Coalfield (for details, see Saghafi, 2012a). These numbers were the basis for what is called Method 1 (see National Greenhouse and Energy Reporting (NGER) documents, 2009).

Over the past decade, several studies have been undertaken to improve the method of fugitive emissions estimation. The effort was culminated in, the development of a mine-specific method (Tier 3 method) to calculate *EFs* (Saghafi, *et al.*, 2003, 2005a, 2005b, 2008; Saghafi, 2010a, 2010b, 2012a). This paper explains this new method, which is described under Method 2 or 3 in the NGER documents (NGER, 2009). A main input parameter in the new emission model is the gas content of coal seams and gas-bearing horizons in overburden and underburden strata. Using the standard method (Standards Australia, 1999) for measuring the gas content of open cut coals may not produce correct results for low-gas-content coals. Hence, a detectable limit of gas content should be agreed upon, or a suitable method of gas content testing for low-gas-content coals should be developed (Saghafi, 2010c, 2012b). In this paper, the effect of using various gas content detectability limits on the evaluation of fugitive emissions is discussed.

THE NEW TIER 3 METHOD FOR ESTIMATION OF FUGITIVE EMISSIONS FROM OPEN CUT COAL MINES

A new approach is used to develop a mine-specific method of estimating fugitive emissions from open cut mines. The approach considers a coal mine as a gas reservoir and assumes that the total volume of emissions from the mine, including exploration boreholes, spoil piles, and transport and haulage of coal products, is equal to the volume of gas initially trapped in the reservoir. If a coal mine advances at a certain regular pace over its life, this approach assumes that emissions would be equal to the volume of gas contained in a column of strata of constant width that includes the overburden and part of the interburden. This column of strata is called the 'gas release zone' (Saghafi, *et al.*, 2005a, 2008; Saghafi, 2012).

Using the new method, the gas release zone is partitioned into a number of gas-bearing horizons that we called 'emission layers' (Saghafi, *et al.*, 2008). The layers are first identified according to their lithology (type of material). The layering can be further refined if the gas content and gas composition vary significantly along the height of the layer (e.g. a coal seam with significant interburden bands).

Figure 1 shows a schematic of a gas release zone in an open cut mine in which the emission layers are identified based on the lithology of the layer (coal, shale and rock). Each layer (i) is characterised by its thickness (h_i), material density (ρ_i), and gas content (c_i) and gas composition. Two coefficients (α_i and β_i) are also attributed to each layer. The production coefficient (α_i) takes on values of 1 or 0 depending on whether the layer is mined ($\alpha_i=1$) or not mined ($\alpha_i=0$). This latter is the case of thin, uneconomical seams in the overburden, and any coal or rock horizon in the underburden. The emission coefficient (β_i), which varies between 0.0 and 1.0, presents the extent of gas release from the layer. A value of $\beta_i=1.0$ indicates that the totality of gas trapped in the layer is released during mining. A value of $\beta_i < 1$ indicates that only part of the layer's gas is released during mining, and a $\beta_i=0.0$ indicates that no gas is released from layer i (the case of a coal seam far below the base of the mine).

Using the above notations, the emission from layer i as a result of mining is:

$$q_i = \beta_i c_i \rho_i h_i \quad (1)$$

q_i is the emission from layer i and is quantified in terms of m^3 of gas per m^2 of ground surface (assuming that gas content is in m^3/t , height in m and density in t/m^3 or g/cc). Hence the total emissions from all n layers would be:

$$Q = \beta_1 c_1 \rho_1 h_1 + \beta_2 c_2 \rho_2 h_2 + \dots + \beta_i c_i \rho_i h_i + \dots + \beta_n c_n \rho_n h_n \quad (2)$$

The quantity Q , expressed in m^3 gas per m^2 ground surface, is the total emissions from coal mine. It is also called emission density in this paper.

Since fugitive emissions are usually expressed in terms of volume of gas liberated per tonne of raw coal extracted, the potential mass of mined coal in the column of strata that forms the gas release zone (Figure 1) should be evaluated. For an individual layer i , the mass of coal that can be produced is:

$$p_i = \alpha_i \rho_i h_i \quad (3)$$

where p_i is the raw coal produced from layer i , and is expressed in tonnes per m^2 of the ground surface. It follows that the total coal production from all n layers is:

$$P = \alpha_1 \rho_1 h_1 + \alpha_2 \rho_2 h_2 + \dots + \alpha_i \rho_i h_i + \dots + \alpha_n \rho_n h_n \quad (4)$$

where P (total coal production from the gas release zone) is expressed in terms of tonnes of coal per m^2 of ground surface.

Hence, the EF for a specific site is:

$$EF = \frac{Q}{P} \quad (5)$$

which gives EF in terms of m^3 of gas per tonne of coal mined (similar to gas content unit).

Using the EF value, the model can take into account the temporary stoppage of mining, in which case the new annual production will be P_r and the emissions volume will be $EF \times P_r$. Note that EF calculated by this method should not be affected by temporary stoppages of coal production. However, if mining is completely stopped, the applicability of this model also stops. This is because emissions would continue, but at a much-reduced rate.

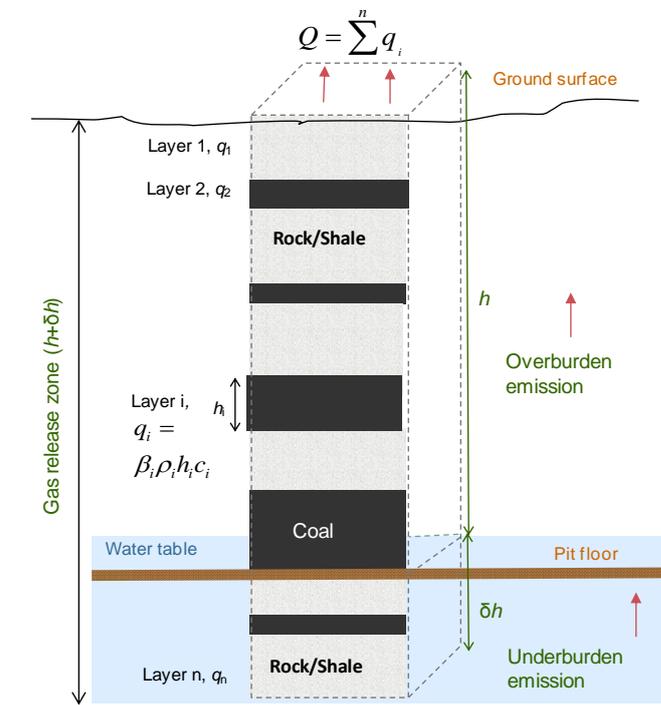


Figure 1 - The new mine-specific emission model showing the gas release zone and emissions layers, not to scale (modified from Saghafi, *et al.*, 2005, 2008; Saghafi, 2012a)

Gas content in terms of CO₂ equivalent

The climate impact of a given mass of a gas emitted to the atmosphere depends on its radiative properties and its atmospheric life span. Global Warming Potential (GWP) is a measure of this impact. GWP is calculated by using the radiative and lifetime of the gas in atmosphere. It varies for different gases according to the time span chosen, reflecting the lifetimes of CH₄ and CO₂ in the atmosphere (Climate Change, 1995). For a time span of 100 years, if CO₂ GWP is taken as 1.0, then the GWP for CH₄ relative to CO₂ is 21 in terms of mass and 8.4 in terms of volume. Note that in later IPCC documents a GWP of 25 for CH₄ is also reported (IPCC, 2007). For greenhouse gas inventory purposes, gas emissions must be reported in CO₂-equivalent (CO₂-e). Therefore, the CH₄ emissions are converted to CO₂ using the GWP factor for CH₄. Another component of coal seam gas in Australia is nitrogen (N₂), for which GWP=0.

If the composition of desorbed gas is known, the measured gas content (C_m) can be converted to CO₂-e gas content (C_{CO_2-e}) as follows:

$$C_{CO_2-e} = \frac{C_m (CO_2 \% + 8.4 CH_4 \%)}{100} \quad (6)$$

Estimation of the emission coefficient β

The value of β indicates how much of the total gas initially in a layer is liberated during mining. It is plausible to assume that any overburden layer releases all its gas ($\beta=1$) in the course of mining. For the coal seams and gas-bearing strata in the underburden, β is less than 1.0, because these layers partially release their gas during mining. We can assume that at a depth of more than 20 to 30 m below the base

of the mine, coal seams retain their gas and $\beta=0.0$ for these seams (Saghafi, *et al.*, 2005, 2008; Saghafi, 2012a). A simple method to estimate β in the underburden is to use a linear function of depth (Saghafi, *et al.*, 2008; Saghafi, 2012a), with $\beta=1.0$ at the base of mining and $\beta=0.0$ at a depth of δh below the base of the pit. Figure 2 shows schematically the variation of β from the ground surface to a distance δh below the base of the pit. Saghafi, *et al.*, (2005, 2008) suggested a value of $\delta h=20$ m for Australian mines. The value of β in the underburden is:

$$\beta = 1.0 - \frac{z-h}{\delta h} \quad (7)$$

Note that the water table and the extent of fracturing of the ground below the pit floor affect the values of β , and can be set to follow other functions (for a more detailed discussion, see Saghafi, 2012a).

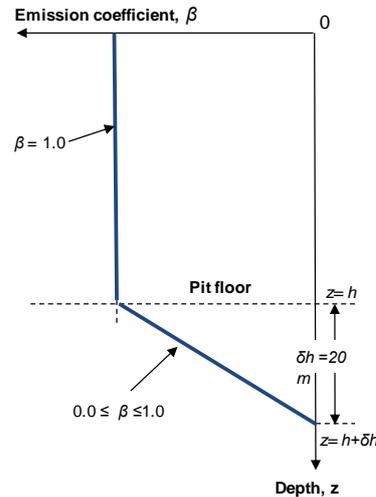


Figure 2 - Emission coefficient β as a function of depth, not to scale (modified from Saghafi, *et al.*, 2005a, 2008, Saghafi, 2012a)

Variability of gas content and gas composition in shallow strata

The large variation in gas content and composition at shallow depths makes the production of a gas distribution model a tedious task. Hence, a number of core holes are required to quantify the distribution of gas in shallow strata. The number of boreholes can be reduced by initially partitioning the mine lease into several 'gas domains' and 'gas zones' (Saghafi, *et al.*, 2008; Saghafi, 2010a, 2010b) in which the local geology, strata layout and hydrology follow similar patterns, so that similar gas patterns can be expected. In each gas zone, at least two boreholes should be drilled and cored for gas content and gas composition. Mine routine exploration boreholes can be used for these measurements. For example, exploration boreholes are subjected to routine geophysical logging, and data such as the thickness of various emission layers, and possibly the porosity of rock layers, can be provided by the log data (Saghafi, *et al.*, 2011). The number of cores from each hole should be at least equal to the number of gas-bearing horizons. Overall, delineating gas zones is a first step in reducing gas drilling. Combining routine exploration drilling with gas testing could substantially reduce the cost of drilling and coring.

Uncertainty of emissions estimate

As discussed, the volume of emissions from a mine site in terms of emissions density, Q , is calculated by summing the individual emissions (q_i) from layers in the gas release zone. If the uncertainty of emissions from the layer i is δq_i , then the uncertainty of the total emissions (emissions density δQ) is:

$$\delta Q = \sqrt{\sum \delta q_i^2 + 2 \sum \sum q_i q_j} \quad (8)$$

Assuming that emission uncertainties of different layers are independent of each other, the second term of square root nullifies and the uncertainty of the total emissions would be:

$$\delta Q = \sqrt{\sum \delta q_i^2} \quad (9)$$

Moreover, assuming that all other measurement errors, except error of gas content, are negligible, it can be shown (Saghafi, 2012a) that the absolute uncertainty of emissions density (δQ) is:

$$\delta Q = \sqrt{\varepsilon_1^2 q_1^2 + \varepsilon_2^2 q_2^2 + \dots + \varepsilon_i^2 q_i^2 + \dots + \varepsilon_n^2 q_n^2} \tag{10}$$

where $\varepsilon_i = \delta c_i/c_i$ is the relative error of measurement of gas content for samples collected from gas-bearing layer i . The relative uncertainty of emissions is calculated by dividing the value of absolute uncertainty by the value of emissions:

$$\frac{\delta Q}{Q} = \frac{\sqrt{\varepsilon_1^2 q_1^2 + \varepsilon_2^2 q_2^2 + \dots + \varepsilon_i^2 q_i^2 + \dots + \varepsilon_n^2 q_n^2}}{q_1 + q_2 + \dots + q_i + \dots + q_n} \tag{11}$$

If the relative errors of gas content for all gas-bearing layers are of similar magnitude, it can be shown that the uncertainty of emissions density is:

$$\delta Q = \varepsilon \sqrt{q_1^2 + q_2^2 + \dots + q_i^2 + \dots + q_n^2} \tag{12}$$

In this equation, ε is an average relative error associated with the measurement of gas content. Depending on the confidence level required, the emissions estimate is reported as $Q \pm k \delta Q$. The coefficient k is the coverage factor; for a confidence level of 95%, $k=1.96$.

EXAMPLE APPLICATION OF THE MODEL TO AN OPEN CUT COAL MINE

The emission model presented here is readily amenable to a spreadsheet calculation. The input data for the model are gas content, gas composition, thickness, density and α and β coefficients for the layer. The output data are emission density (Q in Eq. 2) and emission factor (EF in Eq. 5).

Figure 3 shows a spreadsheet calculation for estimating emissions from a shallow, open cut coal mine, with a maximum depth of ~ 80 m. Coal seams identified as seams 1-3 are to be mined. Seam 4 is a thin seam at a depth of 90 m and is not mined. Using the new method, the strata are first divided into nine layers based on the nature of materials each layer contains. Each coal seam is identified as a single layer. The inputs to the model for each layer are its thickness, average density, average gas content, gas composition, and coefficient α and β . Coefficient α is zero for all layers except seams 1-3. Equation (7) is used to evaluate the value of β assuming that $\delta h=20$ m. Hence for Seam 4, which is located about 10-11 m below the base of the mine, $\beta=0.4$.

Equations (2) to (5) are then used to calculate emission density and EF . Spreadsheet calculation delivers an emission density (Q) of 136.58 m³ CO₂-e per m² of ground surface and an EF value of 8.0 m³ CO₂-e per tonne of coal mined. Note that these calculations use data from a single borehole. Drilling more holes in the area will produce a pattern (contour) of EF in the area, allowing the hypothesis of single or multiple gas zones to be tested.

Emission model inputs												Emission model outputs			
Layer position	Lithology	Depth from (m)	Depth to (m)	Layer height (m)	Density (t/m ³)	Gas content (m ³ /t)	Gas composition (%)		Gas content, CO ₂ -e (m ³ /t)	Layer attributes		Coal production & emissions			
							CH ₄	CO ₂		α	β	p (t/m ²)	q (m ³ /m ²)	δq	δq^2
Overburden	1 Conglomerate & sandstone	0.0	65.2	65.2	2.5	0.05	29.33	70.67	0.16	0	1.0	0.00	25.75	6.44	41.4
	2 Seam 1	65.2	69.3	4.1	1.5	1.06	41.73	58.27	4.32	1	1.0	6.15	26.57	6.64	44.1
	3 Tuff & claystone	69.3	72.6	3.4	2.5	0.05	43.06	56.94	0.21	0	1.0	0.00	1.76	0.44	0.2
	4 Seam 2	72.6	78.5	5.9	1.6	1.27	44.72	55.28	5.46	1	1.0	9.42	51.49	12.87	165.7
	5 Carbonaceous mudstone	78.5	79.9	1.4	2.3	0.15	46.02	53.98	0.66	0	1.0	0.00	2.09	0.52	0.3
	6 Seam 3	79.9	80.9	1.0	1.5	1.39	46.46	53.54	6.17	1	1.0	1.51	9.30	2.33	5.4
Underburden	7 Siltstone, shale & stony coal	80.9	91.6	10.6	2.2	0.20	48.54	51.46	0.92	0	0.7	0.00	15.16	3.79	14.4
	8 Seam 4	91.6	92.1	0.5	1.4	1.68	50.54	49.46	7.95	0	0.4	0.00	2.54	0.63	0.4
	9 Claystone and tuff	92.1	100.9	8.9	2.3	0.10	52.22	47.78	0.48	0	0.2	0.00	1.93	0.48	0.2

Figure 3 - Spreadsheet calculation of the emission factor using the Tier 3 model; seams 1 to 3 are mined

The uncertainty of emissions can be calculated using the quadratic additions method. To simplify the calculation, it can be assumed that the main source of uncertainty is gas content. If all other uncertainties are omitted, Equation (10) can be used. To further simplify the calculation, we assume that for all layers the relative uncertainty of gas content testing is equal and is about 25%. Then Equation (11) can be used, which delivers an uncertainty of about $\pm 16.50 \text{ m}^3/\text{m}^2$ for emission density and an uncertainty of $\pm 0.97 \text{ m}^3/\text{t}$ for *EF*. These uncertainty values are valid for a confidence level of 68%. At a 95% confidence level, the emissions should be reported as:

$$Q = 136.58 \pm 32.33 \text{ m}^3/\text{m}^2 \text{ (CO}_2\text{-e vol)}$$

$$EF = 8.00 \pm 1.89 \text{ m}^3/\text{t} \text{ (CO}_2\text{-e vol)}.$$

To calculate emission factor in terms of CO₂ equivalent mass (CO₂-e mass), a density of 0.00178 t/m³ for CO₂ is used (15°C and 101.325 kPa):

$$EF = 0.014 \pm 0.003 \text{ t CO}_2 \text{ per t coal (CO}_2\text{-e mass)}.$$

LIMIT OF MEASURABILITY OF GAS CONTENT AND EMISSIONS EVALUATION

The limit of measurability is an issue for determining the gas content of low-gas-content coals from shallow seams in open cuts. The standard guideline (AS 3980-1999) was prepared for mine safety and for prediction of outburst potentials and high gas emissions. Therefore, low gas content determination was not an issue, and it has only recently become a focus of research.

Currently, a limit of measurability (or detection limit) of 0.1-0.5 m³/t of gas content of coal is achievable in Australian gas laboratories. The newly published ACARP guidelines for the implementation of NGER Method 2 or 3 for open cut coal mine fugitive emissions reporting (ACARP, 2011), recommend using a detection limit of 0.5 m³/t for gas content of open cut coals when using the gas content data to estimate emissions. This limit of detectability is set irrespective of gas type. If the gas is mainly CH₄ then this limit in terms of CO₂ equivalent is ~4.2 m³/t and if the seam gas is a mixture of 50% CH₄ and 50% CO₂ the limit would be 2.3 m³/t CO₂ e. For gas contents below 0.5 m³/t the guidelines recommend to use a default value of 0.125 m³/t CO₂-e vol (or 0.000 233 t CO₂ per tonne of coal, CO₂-e mass) irrespective of composition of seam gas.

Because of the large differences in the GWP of various gases, using a 0.5 m³/t limit irrespective of gas type and then applying a default value of 0.125 m³/t CO₂-e vol can produce significant differences in the estimated emissions for mines that otherwise have similar magnitudes for their real emissions (in terms of CO₂-e vol).

For instance, assume a coal mine (Mine 1) that extracts a single coal seam at a depth of 70 m. For simplicity of calculation it is also assumed that there is no other significant gas-bearing layers in the overburden or to a depth of 20 m in the underburden. The seam gas is made mainly of CH₄ (90%) with remaining CO₂ (10%). Measured gas content is 0.45 m³/t. Using Eq. (6) the CO₂-e gas content for the mined seam is 3.447 m³/t CO₂-e which is also the *EF* for this mine since the only gas emitting horizon is the mined coal seam. However, because the gas content falls below suggested measurability limit the *EF* for this mine would be the default value of 0.125 m³/t CO₂-e.

Now assume a neighbouring mine (Mine 2), which also extracts a single coal seam at open cut depth of 70 m, but with gas mainly made of CO₂ (90%) with remaining CH₄ (10%). The measured gas content is 0.55 m³/t. The CO₂-e gas content for the mined seam is 0.495 m³/t CO₂-e (Eq. 6), which is also the *EF* for this mine. The gas content for this mine is above the recommended measurability limit and therefore the true *EF* applies. These data reported in Table 1, show that although Mine 2 produces some seven times less CO₂-e gas than Mine 1, it is attributed four times more CO₂-e gas than Mine 1.

Table 1 - Comparison of attributed emission factors for two mines of different gas mixtures using recommended gas content measurability limit of 0.5 m³/t

Coal mine	Measured gas content (m ³ /t)	CH ₄ (%)	CO ₂ (%)	Gas content (m ³ /t, CO ₂ -e)	Emission factor (m ³ /t, CO ₂ -e, vol)
Mine 1	0.45	90	10	3.447	0.125
Mine 2	0.55	10	90	0.495	0.495

A new standard for low gas content testing is urgently required in view of the variation in gas mix in different coal mines. A new standard method should enable measurement of gas content of open cut coals, as well as low-rank coals and coals from shallow underground mines. A joint CSIRO-ACARP study (C18050) to develop a new method for determining the gas content of low-gas-content coals has been completed (Saghafi, 2012b). Two commercial laboratories took part in this study and built two prototypes according to the CSIRO design. The prototype systems were trialled by measuring the gas content of two suites of coals from two open cuts. This study (C18050) showed that it is possible to lower the limit of measurability by one order of magnitude. The study was a first major step in adopting a new method for measurement of the gas content of coals from open cuts. The results from this study will be the subject of a future paper.

CONCLUSIONS

A mine-specific emission model for estimating fugitive emissions from open cut coal mines has been developed. The model meets the requirement of the industry and regulatory bodies for calculating emissions on a mine-specific basis (Tier 3 method). The method, which has been adopted by NGER, is used to establish the NGER guidelines for calculating emissions from open cut mines. The model assumes that gas is emitted from a gas release zone, which consists of gas-bearing horizons or emission layers in the overburden, and the mining-affected section of the underburden. The key inputs to the emission model are thickness, gas content and gas composition of the gas-bearing layers. The outputs of the model are gas emission density, expressed in terms of m^3 of gas released per m^2 of ground surface, and EF , expressed in terms of m^3 of gas released per tonne of raw coal produced.

Since gas content and gas composition are the main input parameters of the model, gas content must be measured in 2–3 locations over a particular site to enable accurate quantification of gas distribution. The standard method of gas content measurement is not suitable for the low-gas-content coals of open cut mines. Therefore, some limits for measurability of gas content are required. A measurability limit of $0.5 \text{ m}^3/\text{t}$ has been suggested. However, such a high limit for low-gas-content coals can lead to erroneous calculations. One issue is the large differences in GWP for various gases. For example, a coal mine with seam gas rich in CH_4 but with gas content below $0.5 \text{ m}^3/\text{t}$ is attributed a $\text{CO}_2\text{-e}$ emission level much smaller than its real emissions. In contrast, a mine with seam gas rich in CO_2 but with gas content above $0.5 \text{ m}^3/\text{t}$ is attributed its true $\text{CO}_2\text{-e}$ emissions. It is suggested that adaptation of a suitable standard for low-gas-content coal is now urgently required to allow proper calculation of fugitive emissions from open cut mines.

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