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Global methane emissions from coal mining to continue growing even with declining coal production

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A B S T R A C T

This paper presents projections of global methane emissions from coal mining under different coal extraction scenarios and with increasing mining depth through 2100. The paper proposes an updated methodology for calculating fugitive emissions from coal mining, which accounts for coal extraction method, coal rank, and mining depth and uses evidence-based emissions factors. A detailed assessment shows that coal mining-related methane emissions in 2010 were higher than previous studies show. This study also uses a novel methodology for calculating methane emissions from abandoned coal mines and represents the first estimate of future global methane emissions from those mines. The results show that emissions from the growing population of abandoned mines increase faster than those from active ones. Using coal production data from six integrated assessment models, this study shows that by 2100 methane emissions from active underground mines increase by a factor of 4, while emissions from abandoned mines increase by a factor of 8. Abandoned mine methane emissions continue through the century even with aggressive mitigation actions.

1. Introduction

Methane is a potent greenhouse gas (GHG) with a global warming potential (GWP) 28–36 times that of CO_2 for a 100-year time horizon (IPCC, 2016; U.S. EPA, 2017b). It also has a short residence time in the atmosphere with a GWP 84 times higher than that of CO_2 over a 20-year period. Methane is a valuable energy source that offers the opportunity to mitigate global GHG emissions (Karacan et al., 2011).

Coal mines are one of the largest sources of anthropogenic methane emissions. Coal production releases methane trapped in coal seams and surrounding strata. Coal mine methane (CMM) is closely linked with coal production; once production is halted and the mine is abandoned, it continues to release methane, referred to as abandoned mine methane (AMM), over a long period of time.

The coal mining industry is estimated to account for 11% of global methane emissions from human activities (U.S. EPA, 2019). However, many scholars argue that current estimates of methane emissions from fossil fuels are underestimated. For example, Schwietzke et al. found that "fossil fuel methane emissions are 60–110% greater than current estimates" (Schwietzke et al., 2016). Similarly, Miller et al. show that global methane emissions might be 1.5 times greater than estimated by the U.S. inventory study (Miller et al., 2013). Though the above-mentioned studies do not focus exclusively on coal, they show that inventories may underestimate methane emissions from fossil fuels.

This study explores three primary questions. First, how do methane emissions from underground and surface coal mines under different coal production scenarios change through 2100? Second, what is the effect of increasing mining depth on global methane emissions through the end of the century? Third, what role does AMM play in total methane emissions from coal mining? This study aims to expose significant granularity to previous studies on methane emissions from coal mining by better capturing and accounting for emissions after mine closure, mining depth, and coal rank (degree of coalification).

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As countries continue to mine coal, mine operators tend to extract coal at greater depths. On average, methane content per ton of coal mined increases with increasing depth. There are numerous studies where researchers use depth-specific emission factors to calculate methane emissions from coal mining. In her pioneering work, Ann Kim estimated global CMM emissions by linking gas content to coal depth and coal rank (Kim, 1977) and this approach has been widely used in other studies, which linked methane emissions with mining depth. Numerous studies have recognized the importance of mining depth in estimating CMM emissions in key coal producing counties or coal basins; additional details on this literature are available in the supplement.

Depth-specific emission factors are used in many international methodologies. For example, the methodology for estimating fugitive emissions from coal mining and handling, developed by the Intergovernmental Panel on Climate Change (IPCC) suggests using three distinct emission factors depending on mining depth. In its Tier 1 methodology, described in the Guidelines for National Greenhouse Gas Inventories, IPCC suggests using an emission factor of 10 cubic meters per metric ton (m^3/t) for depths less than 200 m, 18 m^3/t for depths from 200 to 400 m, and 25 m^3/t for mines deeper than 400 m (IPCC, 2006).

However, most studies simply state the importance of mining depth in determining emission factors, or use depth-specific emission factors. The authors of this paper could not identify any study that links changes in mining depth to changes in emission factors when calculating global CMM emissions (though some studies do this at the national level, for example (MNEC, 2014). A key reason for the lack of such studies has been lack of data (Stern and Kaufmann, 1996). The current study estimates global methane emissions from underground and surface coal production while accounting for the increase in mining depth using several new and compiled data sets.

This study also estimates methane emissions from abandoned coal mines. Most studies ignore AMM because these emissions are believed to be small (Saunois et al., 2016a; Thakur et al., 1994; U.S. EPA, 1990) or because data were not available (Höglund-Isaksson et al., 2016; Kirchgessner et al., 1993; U.S. EPA, 2012). This study presents a novel methodology for calculating AMM emissions; as such, this study is the first attempt to estimate global AMM emissions through 2100 under different coal production scenarios.

This paper is structured in five sections. Following this introduction, Section 2 discusses the methodology for CMM and AMM calculations, data sources, and underlying assumptions. Section 3 presents the main results of estimating CMM and AMM emission forecasts for the reference and mitigation scenarios. Sources of uncertainties in CMM calculations are discussed in Section 4. In Section 5, the authors compare the results with other studies and discuss the implications of this research.

2. Methodology and data

2.1. Model for calculating CMM emissions

A newly developed model – the Model for Calculating Coal Mine Methane (MC2M) emissions – was used to estimate CMM emissions from underground and surface hard coal and brown coal mines. MC2M also estimates global AMM emissions from mines that have ceased production. This model assesses methane emissions under different coal production scenarios related to Shared Socioeconomic Pathways (SSPs) and was used to test the sensitivity of key parameters. The methodology for CMM and AMM emission calculations embedded in the model is described below.

2.2. Methodology for CMM emission calculations

2.2.1. Overview

Global CMM emissions are estimated from several coal ranks including hard underground coal, hard surface coal, and brown surface coal. According to the classifications of the International Energy Agency (IEA), hard coal includes anthracite, bituminous, and coking coal (which is bituminous coal with properties that make it suitable for conversion to coke used for making steel), while brown coal includes sub-bituminous coal and lignite. Total CMM emissions are calculated by multiplying activity data (coal extraction) by the emission factors developed from compiled data on methane storage capacity of coal samples collected from various coal producing basins worldwide.

2.2.2. Coal production

Future coal production is a key parameter for estimating future coal mining-related emissions. For future coal estimates, this study employs projections of coal production through 2100 using two established scenario frameworks that energy modelers commonly use for climate assessments. The first framework, called Shared Socioeconomic Pathways (SSPs) has helped standardize our understanding of uncertainty in future socio-economic development (IIASA, 2017). The SSPs present narratives of alternative socio-economic development, which include future changes in demographics, human development, technology, economy, lifestyle, and other similar trends. The SSP2 scenario is commonly called the "middle of the road" socioeconomic development scenario; this study has used this SSP as the reference scenario for coal production.

The second scenario framework this paper uses are Representative Concentration Pathways (RCPs) (Moss et al., 2010), which show climate mitigation pathways. Specifically, climate mitigation actions and policies would lead to different GHG concentrations in the atmosphere, which in turn result in different levels of radiative forcing (or the amount of heat that the GHG trap). The SSPs and RCPs, thus, show how both socioeconomic changes and policy may affect future energy developments and emissions. The modeling community has standardized both to allow for easier comparison results across studies. For example, SSP2-2.6 means the SSP2 scenario with the RCP 2.6 level of forcing. In other words, SSP2-2.6 assumes that climate mitigation activities limit the increase in forcing to 2.6 Watts per square meter (W/m^2) in 2100 with moderate levels of socioeconomic-driven emissions growth through 2100. SSP2-4.6, on the other hand, would have a forcing level equivalent to about double pre-industrial levels. The modeling community widely uses these pathways to analyze and project future fossil fuel use (Bauer et al., 2016, 2017a, 2017b; Kriegler et al., 2017) and pollution (Rao et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017).

For the reference scenario, this study uses coal production from the SSP2-Baseline scenarios produced by six integrated assessment models (IIASA, 2017). (The SSP baseline scenarios assume no specific climate policy to provide a point of comparison for the policy-related RCP scenarios). This study also tests several RCP mitigation scenarios for the SSP2 pathway to show the effect of climate change mitigation measures. SSP2-2.6 is typically considered a "strong" policy scenario with a low increase in radiative forcing, and SSP2-6.0 is viewed as a "weak" mitigation scenario with a high increase in radiative forcing.

Each of the six models with published SSP2 projections has distinct baseline coal projections due to differences in assumptions and the underlying input data (see the Supplement Tables S1–2). As a result, this paper uses the average coal production data from the six models. The models use fossil fuel resource curves which show an increase in the marginal cost of production as resource bases are exhausted (Rogner et al., 2012).

2.2.3. Underground and surface mining

Methane emission factors depend on many parameters, including mining depth and coal rank. Underground mines are typically much deeper than surface mines and produce higher rank coal. Emissions per unit of coal from underground mines are also larger than those from surface ones.

The authors collected information on coal production methods in major coal producing countries and found significant differences in the share of underground mining. Data on this topic come from several sources, including reports from the United Nations Framework Convention on Climate Change (UNFCCC, 2017) and the Global Methane Initiative (GMI, 2010, 2015), allowing the authors to estimate the average share of underground coal mining in 1990 and 2010. For example, the share of underground coal mining is 95% in China (the largest coal producer) (He and Song, 2012), while it is only 10% in India (the third largest producer) (GMI, 2015). The authors estimate that globally the share of underground hard coal production was 71% in 2010. The 1990–2010 trend was extended through 2100, which results in the share of underground coal production declining to 65% in 2050, and to 60% in 2100.

2.2.4. Rate of change in mining depth

This study draws on data on coal production and mining depth in 1990 and 2010 to estimate the rate of change in mining depth. The authors collected data on mining depth from key coal producing countries (Supplement Tables S3–S7) and combined these with data on underground coal production. The global average mining depth in 2010 was estimated to be 446 m.

Based on these historical trends, this study estimates the global rate of change in depth of underground mines at 0.045 m/EJ/year, which corresponds to about 3 m/year from 1990 to 2010. The rate of change in mining depth does not depend on the coal production scenario and is constant through the period of analysis.

2.2.5. Methane emission factors

There is a predictable correlation between the volume of gas contained in coal and the internal pressure of the coal seam from which it is extracted. Generally, pressure on a coal seam increases with depth, as does the volume of methane contained by the coal. An equation that predicts the amount of gas that may be contained by coal at a certain pressure, or depth, is known as an adsorption isotherm. Isotherms are commonly expressed by mathematical equations are used by engineers and scientists involved in designing coal mines and their gas drainage and ventilation systems. These mathematical equations, which are now an industry standard, were developed by Irving Langmuir (1918). The Langmuir equations are generally accepted as the best model for defining gas sorption capacity of coal (Bustin and Clarkson, 1998; Clarkson and Bustin, 2000; Crosdale et al., 1998). The coal, oil, and gas industries use this model to mathematically describe the capacity of a given coal sample to sorb gas. The model has been used for decades, and consequently, sorption data can be easily compared among coal samples taken from disparate coal ranks and locations. It is defined by the following equation:

$$EF = V_L\,(d^*\,L) / (P_L + d^*L) \quad (1)$$

where,

V_L is the Langmuir volume coal sample
P_L – the Langmuir pressure of that sample
L – Langmuir constant
d – mining depth (meters).

We used the Langmuir isotherm model to estimate the expected gas content of coal. We have compiled results of isotherm testing from many coal basins throughout the world. Coal samples within the database used for this study were collected from North American, South American, Australian, Asian, and European coal basins. Drawing on 250 samples, we estimated gas content of different coal ranks at different depths. To develop the Langmuir adsorption isotherm model for sub-bituminous, bituminous, and anthracite coal ranks, we employ Monte Carlo simulation to develop probability distribution functions. This provides a more statistically robust approach to defining the Langmuir isotherms as it identifies the most likely gas content value for a given rank of coal mined at a given depth. It allows us to account for uncertainty associated with difference in location, geological age and temperature (see Supplement section 2.1 for details). Fig. 1 shows the expected gas content for different coal ranks by mining depth.

The gas content of the current global underground hard coal mix[1] thus is in the range between 13 and 18 m^3/t for mining depths from 450 to 1120 m. For surface mines, the gas content of hard coal is 3–5 m^3/t for depths from 50 to 200 m and 0.77 m^3/t at the constant depth of 50 m for brown coal.

However, the gas content per ton of coal and the emission factor are not equal due to emissions from coal pillars left and from methane in coal seams that occur in surrounding strata (IPCC, 2006; UNECE, 2016). Detailed data from the United States and Ukraine were used to calculate the ratio of relative emissions to gas content. This ratio (also referred to as the emission factor coefficient) is used in the MC2M model to estimate the emissions that result from coal production by inputting the predicted gas content using only the rank of the coal and the depth of mining. Using mine-specific data on depth, coal production, and emission rates across multiple years from U.S. coal reports (EIA, 2017a) and methane emission inventories, the emissions factor coefficient in the United States was estimated to be 1.9. Data from Ukraine's largest coal producing company DTEK show that the emission factor coefficient is 1.5, although it is probable that these data are not compatible with U.S. data because of differences in measurement methods and transparency of reporting (Supplement Figs. S3–4). In China, Ju et al. found that the mining influence coefficient (another name for the emission factor coefficient) is in the range from 1.3 to 2.0 (Ju et al., 2016). In this paper, the average emission factor coefficient of 1.7 is used. The sensitivity of this parameter is discussed in Section 4. To estimate emissions from surface mines, the U.S. Environmental Protection Agency multiplies basin-specific coal production by basin-specific gas content and a 150-percent emission factor to account for emissions from over- and under-burden (U.S. EPA, 2016). It is important to note that most countries do not publish methodologies for coal mine methane emissions measurement procedures; in many cases, mining operators can report data on dates of their choosing, which may not accurately represent emission rates. Thus, there is a distinct possibility that these factors underestimate the emission factor coefficient. The uncertainty is higher for emission factor coefficient values in countries where accepted methodology for emissions measurements and inventories are not uniformly used. In the future, satellite data may allow for independent comparison of emission rates to adjust these factors.

[1] 98% of bituminous coal and 2% of anthracite in 2010 IEA, 2015. Energy statistics of non-OECD countries. International Energy Agency, Paris.

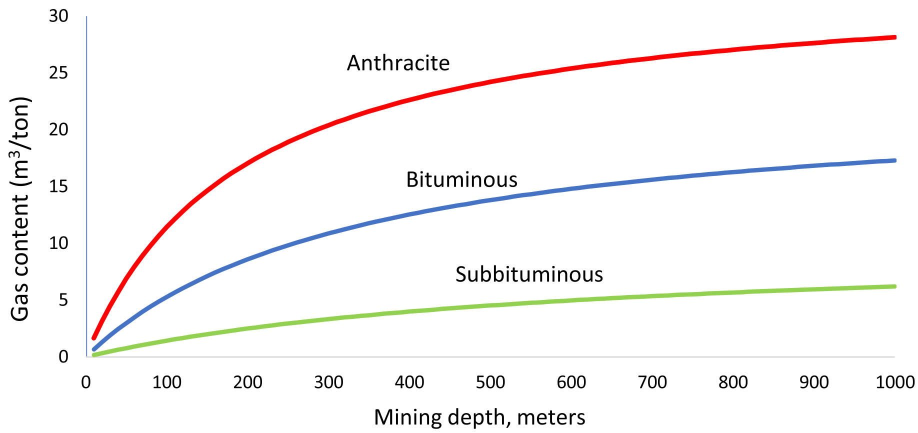

Fig. 1. Gas content by coal rank and mining depth.

2.2.6. Calculating CMM emissions

CMM emissions in any given year were calculated by multiplying global coal production (in billion tonnes categorized by coal rank and mining method) by gas content at a given depth (m^3/tonnes) and the emission factor coefficient. Global methane emissions from coal mining were estimated using Equation (2).

Global coal methane emissions = coal production (tonnes) x gas content x emission factor coefficient (2)

where

coal production is estimated under the SSP2 scenario; gas content is computed using the Langmuir isotherm formula for the appropriate rank coal at the depth of mining; and emission factor coefficient is the ratio of relative emissions over the Langmuir gas content.

2.3. Methodology for estimating AMM emissions

2.3.1. Overview

Initial emissions from abandoned mines in any particular year are calculated using a global abandonment rate and CMM emissions in that year. The AMM methodology accounts for different emissions rates for dry and flooded mines, as described below. It also accounts for AMM emissions from mines abandoned in the past. Total AMM emissions in any given year are the sum of emissions from mines abandoned in that year and AMM emissions from mines abandoned in previous years.

2.3.2. Coal abandonment rate

The coal abandonment rate is the fraction of coal that would have been produced but is not produced because of mine closure (Franklin et al., 2004). This rate can be assumed globally by using data for the coal abandonment rate for the top producing countries. The authors used two different methods to calculate the abandonment rate to account for different types of data available: the first approach uses the ratio of abandoned coal to total coal production and the second uses the ratio of abandoned coal production capacity to total coal production capacity.

Data from U.S. coal reports (EIA, 2017b) on 6500 underground mines over 1983–2015 were used to calculate the abandonment rate in the United States. The authors calculated that the average coal abandonment rate over 32 years was 5.0%. The authors also researched the abandonment rates in other countries. In Russia, the average coal abandonment rate was 4.7% from 1992 to 2013 (Government of the Russian Federation, 2014). China abandoned about 560 million metric tons (Mt) of coal capacity from 2011 to 2016 (Xinhua, 2016). The Chinese government announced its 2016 plan to retire about 4300 coal mines over the next three years; the country still has around 11,000 coal mines with a total capacity of 5.7 billion tons (Reuters, 2016). The abandonment rate in China was estimated to be 4.7%. Data from China and Russia could be used to better understand trends in coal mine abandonment globally.

Since the U.S. data are the most detailed, this study uses the coal abandonment rate in the United States (5.0%) as the global average. Supplement Table S12 shows the underlying data for this calculation. It should be noted that there is lack of data from key coal producing countries about abandoned coal mines.

The coal abandonment rate in the future depends on coal demand. This study assumes that the coal abandonment rate remains constant at 5% per year if coal production increases. Logically, if coal production decreases significantly in the future, the abandonment rate would need to increase because coal companies would not operate non-performing mines. Low productivity mines will be closed and investment in coal production will be concentrated in lower-cost mines. The abandonment rate is, therefore, adjusted to keep the capacity utilization rate, which is defined as the ratio of global annual coal production to global annual productive capacity, at 80–90% in any given year. In the mitigation scenarios, the abandonment rate increases from 5% to almost 7% per year, and coal companies gradually reduce creating new coal production capacity.

Data on CMM emissions from underground mines calculated by MC2M are used as an input for AMM estimates. Once a mine is abandoned, CMM becomes AMM. To estimate the fraction of CMM abandoned in any given year, CMM emissions in that year are multiplied by the average global abandonment rate, representing the volume of emissions from mines abandoned in that year. This volume is then added to the sum of emissions from mines abandoned in previous years to provide a total AMM emission estimate.

2.3.3. Dry and flooded abandoned mines

Once underground mines are abandoned, some of them will flood. Flooding stabilizes the hydrostatic pressure on the coal seams, reducing emissions after that point to near zero (U.S. EPA, 2004, 2016). This study assumes that globally half of abandoned underground mines were dry and another half flooded in 2010. There is little data on the global share of dry and flooded mines, and countries may have different patterns related to the movement of groundwater through the coal bearing rock package. For example, about one third of abandoned mines were flooded in the United

States in 2015 (U.S. EPA, 2017a), while almost all abandoned mines were flooded in Ukraine (Havrylenko et al., 2004). However, globally the authors assume 50% of abandoned mines will be flooding in the future, and this assumption can be adjusted as understanding of this topic increases.

In dry mines, the gas flow rate declines rapidly over the first five years or so, but emissions continue for many decades. Some mines are sealed, which slows the initial rate of emissions, but seals are not effective at preventing atmospheric methane emissions over time (Franklin et al., 2004). Because total emissions remain the same with sealed mines, we treat them like other dry mines for the purpose of this analysis.

In mines that are prone to flooding, methane emissions rapidly decline over less than ten years or so and, once flooded, these mines emit almost no methane. For example, according to U.S. EPA, most mines in the United States that are prone to flooding will become completely flooded within eight years (U.S. EPA, 2016). In Ukraine, flood-prone abandoned mines were completely flooded within seven to eight years (Havrylenko et al., 2004).

The following equation estimates AMM emissions from dry mines in any given year:

$$q = q_i \, s \, (1 + b \, D_i \, t)^{(-1/b)} \tag{3}$$

where,

- q – gas flow rate at time t
- q_i – initial gas flow rate at time zero (t_0) (assumed to be 100%)
- s – share of sealed mines, %.
- t – elapsed time from t_0 (years)
- D_i – initial decline rate, 1/year
- b – the rate of change in the decline rate through time, dimensionless.

For global AMM calculations, we assume that all dry abandoned mines vent methane into the atmosphere. Mine sealing can postpone emissions but cannot prevent mine to release it into the atmosphere unless it is captured and utilized.

The decline in methane emissions from flooded mines can be expressed by the following equation:

$$q = q_i \, e^{(-t \, D_i)} \tag{4}$$

where,

- q – gas flow rate at time t
- q_i – initial gas flow rate at year of abandonment (t_0)
- t – elapsed time from t_0 (years)
- e – the constant (2.71828), the base of the natural logarithm
- D_i – decline rate, 1/year.

Table 1 shows the parameters D_i and b for dry and flooded mines used in this study.

Table 1 shows parameters of the decline curves based on the data from various coal mine basins in the United States. This approach is also used in other countries. For example, Fernando (2011) used a similar methodology to assess the decline in AMM emissions in the United Kingdom.

Table 1
Parameters of decline curves for flooded and dry mines.

Mines status	Variable	Value
Flooded	b	2.017
	Di	0.302
Dry	Di	0.672

Source: Authors' calculations.

Fig. 2 shows assumed methane decline curves for abandoned dry and flooded mines over time. The Supplement describes the methodology for calculating the decline in the initial emissions from abandoned mines.

As noted, emissions from flooded mines become almost negligible eight years following abandonment while emissions from dry mines last for decades. To calculate AMM emissions in any given year, one needs to sum AMM emissions from mines abandoned in that year and emissions from mines that were abandoned in the past. The authors use coal production data from 1971 (the earliest available global coal production data by rank from IEA) to calculate residual emissions in 2010 and beyond from mines that were abandoned in 1971–2009. The method described above was also used to estimate future abandoned coal to produce estimates of future AMM emissions.

2.3.4. AMM calculation

AMM emissions are calculated as the sum of emissions from all dry and flooded coal mines abandoned since 1971 (the first year when coal production data are available from the International Energy Agency).

Total methane emissions from coal mining is the sum of CMM emissions from hard coal underground mines, hard coal surface mines, brown coal surface mines, AMM emissions from dry underground mines and AMM emissions from flooded underground mines.

3. Results

This study indicates that CMM and AMM emissions in the future will likely be significantly higher than previous studies have found, with the detailed analysis of mining depth, AMM and other such factors the primary reason for these differences. This section provides results for both our reference scenario and the mitigation scenarios.

3.1. CMM and AMM in the reference scenario

To estimate CMM emissions by 2100, the MC2M model uses data on future coal production from the SSP2-Baseline scenarios, the rate of change in mining depth, and mining-depth derived emission factors. This study estimates total CMM emissions from underground and surface mines at 103 billion cubic meters (bcm) in 2010. Underground coal mines and surface hard coal mines account for 91% and 9% of global CMM emissions, respectively. CMM emissions from brown coal are estimated to be about 1%.

Based on the SSP2-Baseline scenario for coal production, total CMM emissions reach 432 bcm per year in 2100. These estimates are based on methane released, but depending on policies, gas that will otherwise be emitted may be used for energy rather than released to the atmosphere. Today, most countries release the majority of their CMM to the atmosphere. The share of emissions from surface mines in total CMM emissions increase to 23% in 2100 (Fig. 3). In these projections, the depth of underground mines increases to 1120 m by 2100.

It should be noted that our model does not factor in the utilization of CMM and AMM. The utilization of methane from coal mines decreases the volume of methane released into the atmosphere; however future projections of methane utilization is beyond the scope of this study. Today, only a few percent of total CMM emissions are utilized given that the vast majority of emissions are low-concentration emissions in ventilation air systems. Appropriately developed and implemented policies can impact

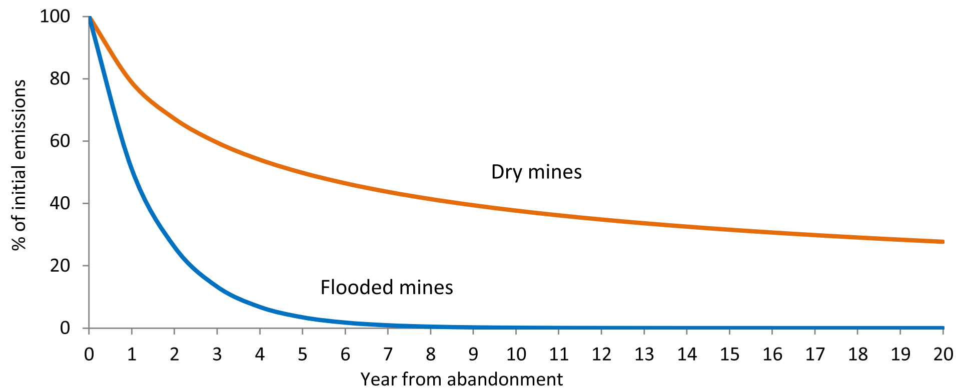

Fig. 2. Assumed AMM emission reductions over time from dry and flooded mines.

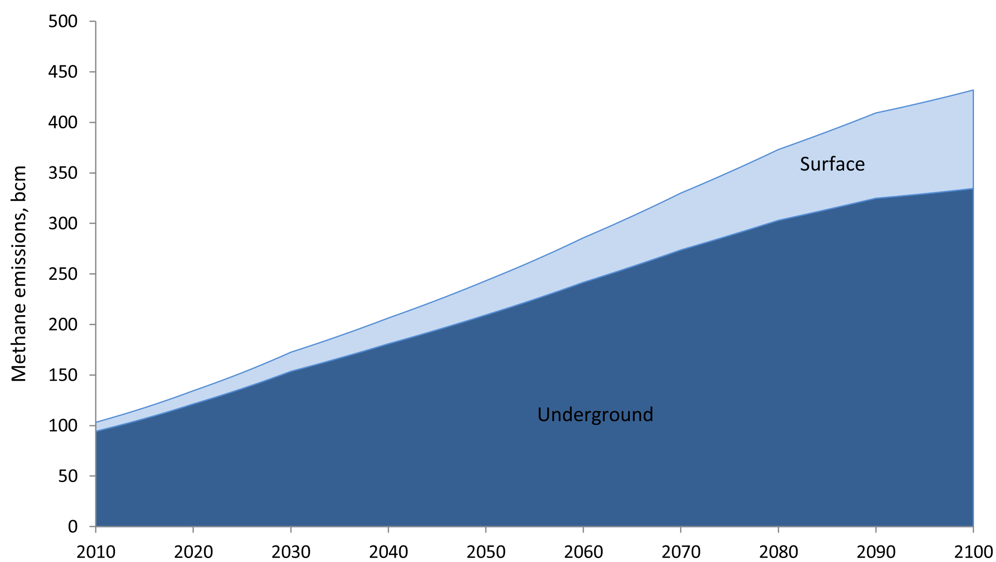

Fig. 3. Global CMM emissions from underground and surface mines, 2010 to 2100, bcm (Based on the SSP2-Baseline scenario, average from the six models).

utilization rates. This study does not include coalbed methane production, which involves virgin coal seams where no mining is planning in the near to medium term.

This study is the first attempt to calculate global AMM emissions (Fig. 4). Previously, AMM emissions were assumed to be included in the total emissions from coal mining by using a single emission factor. This study estimates global AMM emissions to be 22 bcm in 2010. AMM emissions are projected to increase to 75 bcm in 2050 and 162 bcm per year in 2100.

This study estimates how much the increasing depth contributes to an increase in methane emissions from underground mines. To isolate the effect of increasing mining depth on methane emissions, the authors also calculated CMM and AMM emissions using a constant CMM gas content of 13.2 m^3/t for the estimated average depth of mining in 2010 (446 m). In this constant emission factor scenario, we apply the same gas content for underground mining through 2100, while all other assumptions remain the same. The results show that in 2050, CMM emissions in the reference scenario are 21% higher than in the constant emission factor scenario; this difference increases to 53% by 2100. AMM emissions in the reference scenario are 11% and 25% higher than in the constant emission factor scenario. This highlights the importance of accounting for increasing mining depth and, as a result, increasing emission factors in estimating future methane emissions from coal mining.

Supplement Tables S13–14 show data on coal production, mining depth, emission factors, and CMM emissions from 2010 to 2100. Supplement Fig. S5 shows CMM and AMM emissions using coal production data for the SSP2-Baseline scenario from the six integrated assessment models.

3.2. CMM and AMM in mitigation scenarios

In addition to the reference scenario, this study also estimates CMM and AMM emissions in the mitigation scenarios. The authors use coal production data from two climate change mitigation scenarios with forcing levels of 2.6 W/m^2 (strong mitigation, SSP2-2.6) and 6.0 W/m^2 (weak mitigation, SSP2-6.0) (Fig. 5). GHG emissions in the SSP2-2.6 scenario limit global warming to an increase of around a 1.5 °C (with about a 50% probability) compared to the pre-industrial levels, while emissions in SSP2-6.0 are far above this level (leading to a temperature increase of about 3 °C). These previously published mitigation scenarios assume a range of policies and actions to reduce emissions, but they do not specifically target CMM and AMM emissions.

CMM emissions follow the trajectory of coal production. AMM emissions instead grow or remain flat even if coal production decreases sharply (Fig. 6). The MC2M results show that AMM emissions will continue to increase for decades with declining coal production.

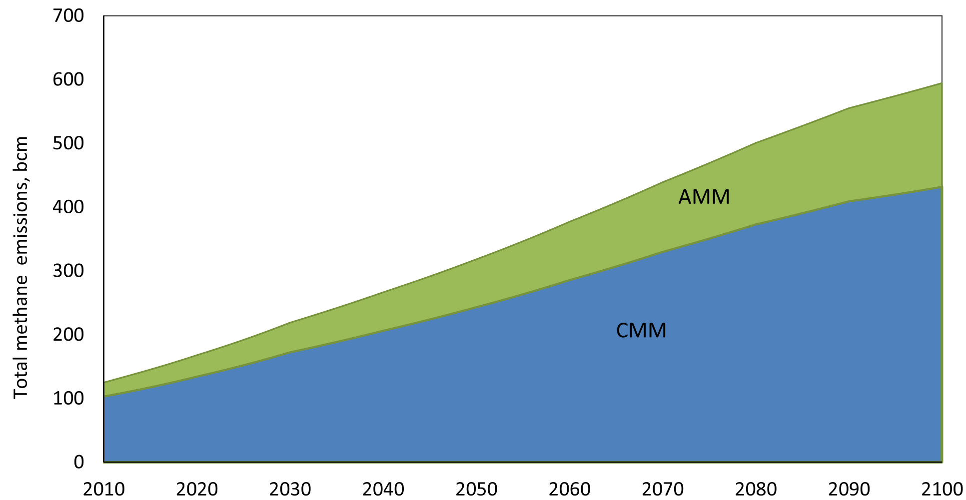

Fig. 4. Global methane emissions from coal mining, 2010 to 2100, bcm.

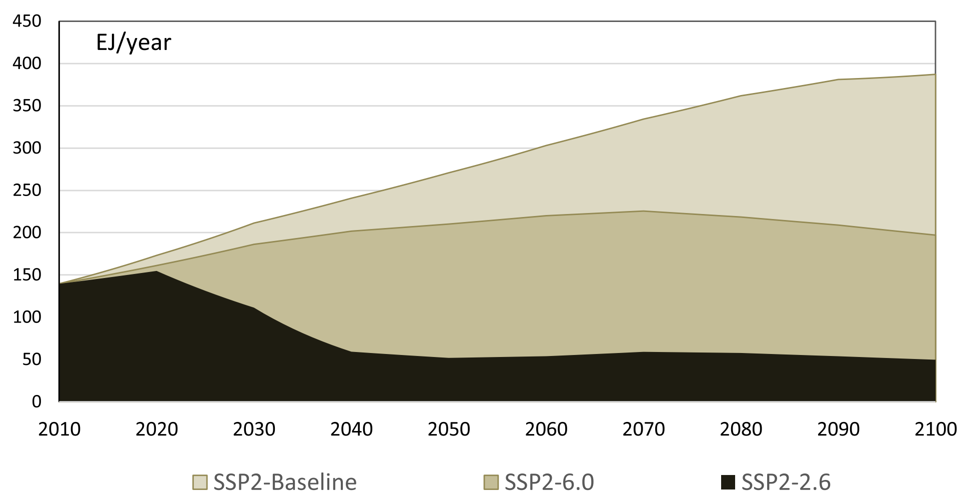

Fig. 5. Global coal production in the SSP2-Baseline and two mitigation scenarios, 2010 to 2100, EJ.

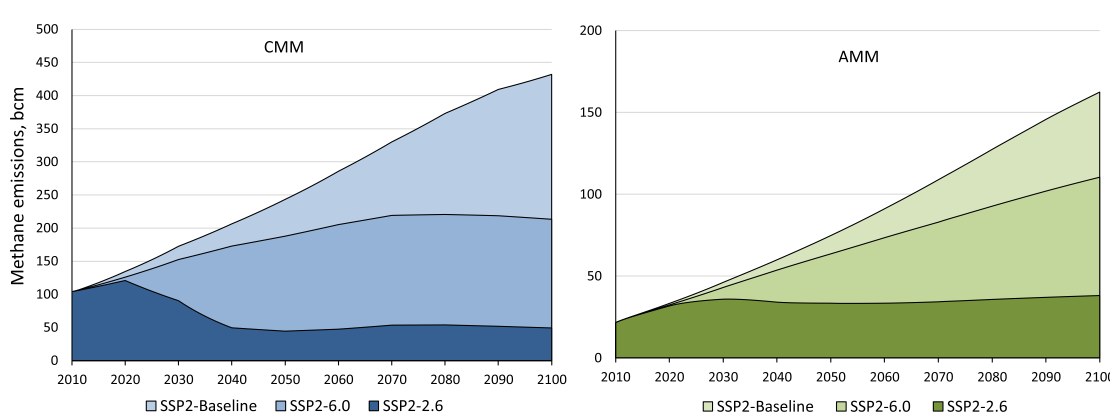

Fig. 6. Global CMM and AMM emissions in the mitigation scenarios, 2010–2100, bcm. Note the difference in scales.

The baseline estimate (SSP2-Baseline) for coal production by 2100 shows that underground coal production increases by a factor of 2.8 relative to 2010, while CMM emissions from underground mines increase by a factor of 4.2. AMM emissions are projected to increase by a factor of 7.5 by 2100.

4. Uncertainty

To assess the effect of key uncertainty factors on CMM emissions, the authors compared emission results in 2050. Since the study estimates future emissions, the authors estimate the importance of uncertainty factors in the foreseeable future when one can make reasonable assumptions about the uncertainty of key factors used in emission calculations.

The assumptions and inputs with the greatest uncertainty in this study are: 1) emission factor coefficient (ratio of specific emissions to gas content) in underground mines; 2) future coal production; and 3) the share of underground coal in future coal production. These three uncertainty factors are briefly discussed below (Supplement Table S16 shows the full results of the sensitivity analysis). Fig. 7 shows the most sensitive parameters in the CMM calculations in 2050. The figure shows changes in CMM emissions from the reference scenario (central estimate) in 2050 (bcm per year)(see Fig. 8).

The most important uncertainty factor is the emission factor coefficient. As mentioned before, this study uses a global average coefficient of 1.7. The low and high estimates of the coefficient were used to test the sensitivity of CMM emissions in 2050. The low estimate is 1.0 (the gas content equals the relative emission value) and the high is 2.3 (the highest average annual ratio found in the data from the United States, 2011). It is important to note that the availability of statistical data outside the United States linking gas content with emissions is very limited. The authors also included Ukrainian data because they are the only available and consistent dataset available outside of the United States, but we recognize that differences in mining techniques across countries likely affect emissions. However, the Ukrainian data also show some mines with extremely low levels of emissions (Fig. S4), and the average emissions rate from the Ukrainian mines is below what one would predict using IPCC emission factors (Table S10), though Ukrainian mines are typically very gassy. It is also likely that there are different methods of measuring and estimating emissions from mines across countries. Mine emissions typically involve a combination of measured data on the methane content of ventilation air, ventilation air flow rates and methane released through boreholes. Data may be measured at different intervals, while emissions can vary over time. There may also be issues regarding how coal production is measured (some countries use data for washed coal, while others use data for raw coal; this also could impact the ratio of emissions to a tonne of coal. Using the range of estimates described above, CMM emissions could be 35% below to 31% above the reference estimate. Moreover, data from the United States show that the emission factor coefficient increases with increasing mining depth (Fig. 8). In the future, as coal mines get deeper, the emission factor will likely increase, which this study has not taken into account because of limited international data. Additional research to improve estimates of this coefficient is needed to better constrain both current and past emission estimates.

Future coal production, the second most important uncertainty factor, is a key variable in all estimates of future methane emissions from coal mining. As noted above, the reference scenario in this study uses coal production from SSP2-Baseline. To test the sensitivity of this parameter, data from the lowest and highest estimates of coal production in 2050 among all SSP2-Baseline scenarios (MESSAGE-GLOBIOM and GCAM respectively) were used to calculate CMM emissions. Using the individual model results, CMM emissions in 2050 range from 25% below to 31% above the average SSP2-Baseline result presented in this paper. Historical data, however, show that the increase in global coal extraction in recent years was slower than the published SSP2-Baseline scenarios show. Recent data show that global coal production has remained flat over the past several years. Because this study uses publicly available runs from a range of models using consistent scenarios, these results may not capture the decline in coal production in the past five years. Specifically, the published results from these models typically use 2010 as a baseline year. A few recent studies that use a 2015 baseline show lower results in 2050. For reference, IEA's latest projections using a more recent baseline show that with current technologies, global coal consumption will be constrained in the future (IEA, 2019). The U.S. Energy Information Administration's (EIA) most recent estimate (with a 2015 baseline) projects that global coal production will increase by only 6% from 2015 to 2050 (EIA, 2019). Integrated assessment models try to look at longer-term economics and focus less on short-term trends. Supplement Table S15 and Figs. S8–S9 show the results for coal production, CMM and AMM emissions through 2100 using coal production data from the SSP1-Baseline and mitigation scenarios, which are more similar to the recent coal production estimates from the IEA and EIA through 2050.

Another important factor in uncertainty is the share of underground coal in total coal production. One EU study shows that the share of surface mining will continue increasing and may reach parity with underground mining (Energy Edge Limited, 2007), however, models rarely factor in this trend. For example, the

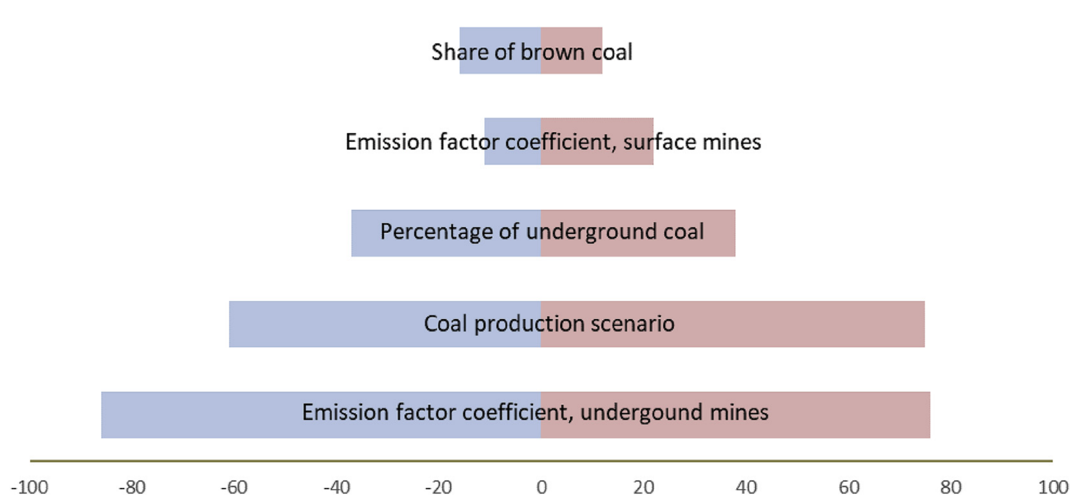

Fig. 7. Effects of key uncertainty parameters on future methane emissions in 2050 (bcm per year).

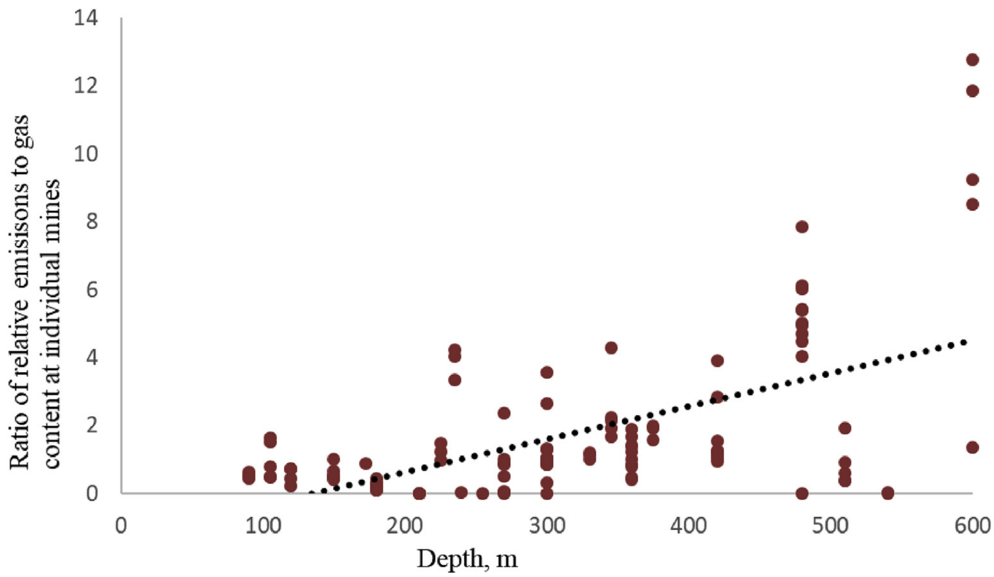

Fig. 8. Emission factor coefficients and mining depth (data from U.S. longwall mines).

Greenhouse gas - Air pollution Interactions and Synergies (GAINS) and 2019 EPA study on global non-CO_2 greenhouse gas emission projections, keeping the split constant through 2050 (Höglund-Isaksson et al., 2016; U.S. EPA, 2019). As noted above, the share of underground coal in hard coal production is 71% in 2010. This study tests various assumptions for the share of underground coal in hard coal production in 2050—65% (central estimate based on extrapolation of the historical trend), 50% (low) and 80% (high). Using the low and high estimates of the share of underground coal mining, CMM emissions in 2050 are estimated to be from 15% below to +16% above the reference value.

Despite these uncertainties, the model uses the best available data to help understand trends of methane emissions from the coal sector. Detailed data on key parameters of the model help reduce the uncertainty of emission estimates.

5. Discussion and conclusions

Three important conclusions emerge from this study. The first is that future CMM and AMM in this study are significantly higher than those in previous studies given the detailed analysis. Second, even with aggressive climate policies, AMM resources are likely to grow, their role in total methane emissions will increase, and AMM will be emitted if they are not utilized. Third, the datasets put together for this paper may provide insights for improving future inventories. The discussion below provides an additional explanation on each of these points.

5.1. Higher estimates than previous studies

This study estimates that total methane emissions from coal mining (CMM and AMM) in the base year (2010) were higher than previous studies show (Table 2). CMM emissions in this study are estimated to be 24% higher than data from the Community Emissions Data System (CEDS), the most recent inventory. When accounting for AMM emissions, the total methane emissions from MC2M are 50% higher than CEDS.

The MC2M model uses nuanced assumptions for coal extraction method, coal rank, and evidence-based depth-related emissions factors, while many models oversimplify their assumptions. For example, and CEDS are the Emission Database for Global Atmospheric Research (EDGAR) bottom-up emissions inventories, which use country-specific emissions factors but do not distinguish between underground and surface mining. GAINS distinguishes between underground and surface coal production but does not look into coal rank. A 2019 EPA study assumes that all hard coal is produced underground (except for countries which submit their reports with more detailed information to UNFCCC), whereas, in reality, some hard coal is produced above the ground (U.S. EPA, 2019).

The difference between CMM results in this study and estimates from other models increases in the future. In part, this is a result of the increasing emission factors and a more detailed understanding of potential future AMM emissions. As noted above, accounting for increasing mining depth increases CMM estimates in this study by 21% in 2050 and 53% in 2100. Supplement Figures 6-7 provide additional details about this comparison.

To compare the estimates of future methane emissions from coal extraction by 2100, the authors obtained data from an inter-model comparison study (Harmsen et al., 2018), which is part of the EMF30 project (EMF, 2017) as well as two other studies of long-term emission. Harmsen et al., 2018 project methane emissions from several sectors including coal mining by 2100 (Table 3).)

All the models produce coal data using the SSP2-Baseline scenario and account for methane utilization. The utilization of methane from coal mining is the only factor that lowers the emission estimates in the study by Harmsen et al., 2018.

The problem of coal mine methane emissions has recently gained the attention of influential international organizations. For example, the International Energy Agency estimated global CMM emissions in 2018 at 40 Mt methane (59.7 bcm) (IEA, 2019), though it highlights that there is a high degree of uncertainty in estimating the level of CMM emissions that occur today. The fact that the International Energy Agency looked in detail at the levels of methane emissions from coal mining highlights the importance of CMM and AMM in global anthropogenic emissions.

5.2. AMM emissions increase in the future even with robust climate mitigation

The results show that regardless of future coal production scenario used by the model, AMM emissions will increase in the future.

Table 2
Estimates of methane emissions from coal mining in 2010 (bcm).

Study or model	CMM emissions, bcm (original reported value)	Notes	Reference
EPA	58.3 underground and 1.2 surface (820 $MtCO_2e$ underground and 17.1 $MtCO_2e$ surface)	Integrated emission model	U.S. EPA (2019)
Schwietzke et al.	63.1 (42.9 (36.9–53.8 Tg)	Bottom-up calculations	Schwietzke et al. (2014)
Saunois et al.	60.3 (range 38–74) (41 (range 26–50) Tg)	Synthesis of bottom-up models and inventories Average data for 2003–2012	Saunois et al. (2016b)
EDGAR v4.3.2	57.9 (39.4 Tg)	Greenhouse gas dataset	EDGAR (2017)
CEDS v 5.1.17	83.0 (56.4 Tg)	Emission inventory	Hoesly et al. (2018)
MC2M	103	CMM only	Current study
MC2M	125	CMM + AMM	Current study

Table 3
Projections of future methane emissions from coal mining, bcm.

Methane emissions, bcm/year	2010	2050	2100
AIM/CGE	69	90	111
DNE21+ V.14	85	136	164
ENV-Linkages	55	68	–
IMAGE	78	128	264
MESSAGE-GLOBIOM	74	114	179
POLES	78	96	75
REMIND	70	28	23
GCAM 4.3	78	174	257
GAINS	57	–	–
MC2M (CMM + AMM)	125	318	594
MC2M-constant EF (CMM + AMM)	125	268	412

GAINS (Höglund-Isaksson, 2012); all other results are from (Harmsen et al., 2018).
Source: MC2M – current study; GCAM – authors calculation;

AMM emissions accounted for 17% of the total methane from coal mining in 2010. For comparison, data reported to the United Nations Framework Convention on Climate Change (UNFCCC) from key coal producing countries show that the share of AMM in total methane emissions from coal mining in the latest available year (2015) was 1% in Germany, 2% in each Australia and Poland, 11% in the United States and 34% in the United Kingdom (UNFCCC, 2017). AMM emissions can be difficult to inventory because of ownership issues, measurement problems, the extent of mine flooding, and other factors. Because AMM emissions grow faster than CMM, the share of AMM in total methane emissions may increase to 23% by 2050 and 27% in 2100 in the reference scenario.

The share of AMM emissions increases even faster in climate mitigation scenarios. AMM emissions continue throughout the century even under the strong policy scenarios, which limit CMM emissions as a result of declining coal production. Because of the increase in AMM emissions and the decrease in CMM emissions in the mitigation scenarios, the relative role of AMM in these scenarios is even more significant than in the baseline.

This study estimates that the share of AMM emissions increases in all scenarios in the future relative to 2010. By the end of the century, AMM's share in total methane emissions from coal mining is projected to reach 34% in the SSP2-6.0 scenario and 44% in the SSP2-2.6 scenario. It should also be noted that AMM calculations in MC2M do not account for residual AMM emissions from coal mines abandoned before 1971. The model results show that these residual emissions from older dry mines are relatively small and may account for an additional 10% of AMM in 2010.

This conclusion highlights the need to address the problem of AMM emissions. Coal producing countries should promote utilization of CMM and AMM to minimize their release into the atmosphere.

5.3. Opportunities for improving future CMM and AMM inventories

This study reveals significant data gaps in estimates of methane emissions from coal mining. Countries do not provide data on coal production by coal rank, method, and depth in a single database. Country-specific emissions factors developed by rigorous measurement often are not available even for the largest coal producing countries. Countries do not regularly report the mining depth of coal mines. If countries collect additional data on emissions, gas content and mining depth at specific mines, it will be possible to further enhance our understanding of both current and future emissions. This would reduce the uncertainty of emission factors (specifically, emissions compared to gas content).

For AMM calculation, it is important to know whether the mines are dry or flooded, what the abandonment rate is, and what the level of initial emissions in the year of abandonment was, though the latter may be difficult to determine. Improved data on abandoned mines, as well as the flooded status, would improve the accuracy of AMM estimates.

The methodology and integrated datasets developed in this study could be used to improve inventories of methane emissions from coal mining. The detailed data on gas content at different depths, combined with ratios to convert gas content to emissions, can help countries cross-check their Tier 2 and Tier 3 inventory estimates. They could also provide an alternate, more detailed option for countries that have data on the depth of their mines but do not have mine-specific emissions.

While working on this study, the authors analyzed AMM data which countries report to the UNFCCC. The results imply that many countries may be underreporting their AMM emissions (see Supplement, section 3.4). The AMM methodology presented here could help countries more completely estimate their AMM emissions, particularly when they lack measured data from individual mines. This is important as AMM emissions will grow in the future.

Using emission factors which depend on mining depth and coal rank and analyzing how it changes over time, could help countries with limited measured emissions understand whether they have consistent CMM estimates over time.

5.4. Conclusions

Methane is a valuable energy resource, and more accurate projections of future CMM and AMM emissions can give a better understanding of the economic potential of this energy resource. More accurate projections can provide a better understanding of the mitigation potential and cost of climate mitigation strategies. CMM and AMM utilization projects tend to be large and even with limited numbers of projects it is possible to capture and use a significant share of methane emissions from coal mining. The number of abandoned coal mines increases every year and offer opportunities for non-coal mine project developers to capture and utilize the gas. Utilization of CMM and AMM is also important because of their many co-benefits, including mine safety and improved air quality. AMM emissions will remain significant by the end of the century regardless of future coal production.

Declaration of competing interest

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

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Nazar Kholod: Software, Data curation, Validation, Formal analysis, Writing - original draft. **Meredydd Evans:** Conceptualization, Investigation, Project administration, Writing - review & editing. **Raymond C. Pilcher:** Conceptualization, Methodology, Data curation, Software, Formal analysis, Writing - review & editing. **Volha Roshchanka:** Conceptualization, Data curation, Writing - review & editing. **Felicia Ruiz:** Supervision, Writing - review & editing. **Michael Coté:** Resources, Validation, Writing - review & editing. **Ron Collings:** Resources, Writing - review & editing.

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Appendix A. Supplementary data

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