# System and Process Understanding of Mine Gas Release of Closed Hard Coal Mines in the Context of EU Methane Regulation

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**Abstract**

Even after the closure of a mine, degassing of methane on the surface is observed. EU regulation 2024/1787 obliges companies to continuously measure and reduce these emissions, which is a major challenge given the thousands of degassing sites (shafts, adits, boreholes, faults) in the Ruhr region alone. Integrated monitoring, including hydraulic and geochemical analyses, can shed light on release mechanisms. The rise of mine water level can be an effective method to control degassing. This contributes to the regulation of methane emissions and supports compliance with the new EU emission reduction targets for the energy sector.

**Keywords:** Mine gas release, mine water rebound, methane, integrated monitoring

## Introduction

Methane is released from fossil deposits, e.g. those of lignite and hard coal, as well as of oil fields, moors and swamps; it is also released during the exploitation and decomposition of organic materials (e.g. in agriculture or landfills). In the atmosphere, it acts as a greenhouse gas that is harmful to the climate and it harbours an equivalent of global warming potential (GWP) that is between 28 and 80 times higher (EC 2024) than that of carbon dioxide ($CO_2$). In 2020, almost 13 billion tons (EC 2021) of $CO_2$-equivalent methane was released into the atmosphere worldwide. The largest contributor was agriculture and livestock farming (47%), followed by the energy sector (oil, natural gas, coal; 28%), waste management (13%) and other industries (12%). The Global Methane Initiative (GMI, US EPA 2025) states that in 2020 it was China which made the largest contribution to global methane emissions with 18%, followed by Russia with approx. 11%, the US with 8% and India with 7% (GMI, US EPA 2025).

There are regular observations of degassing processes at the surface of (former) mining areas; during the active mining stage, the mine gas flows into the mine workings through loosened rock above and below the seams. For safety purposes, this mine gas is diluted using technical measures such as fresh air supply (ventilation), or it is extracted from bore holes (pre-degassing).

In the post-mining phase, methane continues to degas from open mine workings, the deposit itself, and adjoining rocks. A proportion of the mine gas remains in the mining areas as natural residual gas. Even where mine workings are flooded, methane may continue to degas. At low barometric pressure the mine gas escapes from the mine workings to the atmosphere through a network of fissures that has occurred either naturally or as part of the exploitation. This migration can be enhanced by the rise of the mine water level which often results from the adjusted mine water pumping during the post-mining stage. In some cases, this effect is often not fully recorded, analysed or clearly communicated to the public. This approach leads repeatedly to annoyance and fear among the population, and this in return has negative effects on the public acceptance or the natural environment.

On 15/11/2023, the EU Parliament and the EU Member States agreed on a submission to pass a regulation on reducing methane emissions; this regulation is based on the EU-wide strategy to reduce methane emissions of 14/12/2020 and on a draft regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector of 15/12/2021. The EU Regulation 2024/1787 of the European Union aims at reducing methane emissions, improving the air quality, and strengthening the global leadership of the EU in the fight against climate change.

## Degassing behaviour of an underground mine during mine water rebound

Methane gas from abandoned mines can reach the surface through the rock mass (which consists of hard coal seams, overburden, faults/remoulding) and via boreholes and degassing pipelines. The overburden often shows different types of consolidation, porosity, crevasse formation and permeability. Due to crevasses and fissures in the overburden mine gas can naturally escape into the atmosphere. Because of the low permeability, the flow resistance inside the coal seams and overburden strata is relatively high compared to that in the open mine workings. Mostly, there is a slow flow in a porous or fissured medium at low speed and Reynolds number.

If a seam comes in contact with the surface due to galleries, shafts, crevasses or fissures, the methane content in the hard coal is reduced until the gas pressure inside the seam is identical to the atmospheric (air) pressure. This process is stopped when mine water accumulates at the hard coal or a water column forms. In this case, the degassing of the methane can be reduced; the mine water acts as a barrier and prevents the exchange of the methane from the coal to the ambient air. Thus, the pressure gradient decreases and the potential release of methane is reduced. This process can result in less methane escaping to the surface.

According to an examination by Krause & Pokryszka (2013), the degassing velocity is reduced by a factor of 9 as soon as the seam is flooded with mine water and hydrostatic pressure is exerted on the hard coal. This result shows that the presence of mine water influences the degassing velocity and considerably reduces the release of methane. A seam with a gas pressure of 10 bar can no longer degas at a water column of 90 m (corresponding to 9 bar) and the additional atmospheric pressure of 1 bar. The pressure inside the water column and the atmospheric pressure exceed the pressure inside the seam and, as a result, no further methane is released. An equilibrium is created, and the degassing process is stopped. Although methane may dissolve in the mine water and move also towards the surface through diffusion in water, the diffusion velocity of methane in water is lower than that of methane in air, to be precise, by a factor of approx. 10,000 (Stephan *et al.* 2019). This means that the methane molecules move much slower in mine water than in air; consequently, the degassing of methane from mine water happens at a much slower pace and can be substantially delayed.

## Isotope geochemistry of methane

The isotopic composition of methane can provide insights into its mode of formation. Methane can be generated either biogenically or thermogenically. In biogenic methane production, microorganisms known as methanogens or methane producers are involved. These organisms obtain energy either through the fermentation of acetate or the reduction of carbon dioxide using hydrogen (Whiticar *et al.* 1986). Since these microorganisms preferentially use the lighter carbon isotope $^{12}C$ for their metabolism, isotopic fractionation occurs, leaving a characteristic signature in the carbon of the methane. The isotopic composition is expressed in delta notation. This represents the relative difference between the isotopic ratio in a sample and a standard (PDB, Peedee Belemnite), where the ratio of the heavier to the lighter isotope ($^{13}C/^{12}C$) is measured. The $\delta^{13}C$ values for biogenic methane typically range between -110‰PDB and -50‰PDB (Whiticar *et al.* 1986).

$$\partial^{13}C = \frac{\left(\frac{^{13}C}{^{12}C}\right)_{Probe} - \left(\frac{^{13}C}{^{12}C}\right)_{Standard}}{\left(\frac{^{13}C}{^{12}C}\right)_{Standard}} \times 1000\,‰$$

In thermogenic methane formation, organic material (plant matter, aquatic organisms) is thermally decomposed under high-pressure and high-temperature conditions (Tissot & Welte 1984). Thermogenic methane is isotopically heavier, with $\delta^{13}C$ values typically ranging between – 50‰PDB and -30‰PDB (Tissot & Welte 1984). During thermogenic methane formation, higher hydrocarbons such as ethane, propane, and butane are also produced (Tissot % Welte 1984). Thus, the ratio of methane to the sum of ethane and propane can serve as an additional indicator for distinguishing between thermogenic and biogenic methane. Thermogenic methane has a characteristic value of <100 (Whiticar *et al.* 1986), while biogenic methane shows values >1,000 (Bernard *et al.* 1977). In biogenic metabolic activities, higher hydrocarbons are formed only in trace amounts.

Microbial degradation of methane also influences the isotopic signature. Microorganisms that oxidize methane and convert it to carbon dioxide or bicarbonate preferentially use the lighter $^{12}C$ isotope (Barker & Fritz 1981). As a result, the remaining methane becomes increasingly heavier, which can lead to pseudo-thermogenic isotopic values (Humez *et al.* 2019).

Other processes affecting the isotopic signature of methane include its migration (diffusion) and the desorption and adsorption of methane onto coal (Gaschnitz 2001). Both processes lead to isotopic fractionation, i.e., the preferential mobilization of the lighter $^{12}C$ isotope.

## EU methane regulation

In October 2020, the European Commission adopted an EU strategy to reduce methane emissions ('the Methane Strategy') setting out measures to cut methane emissions in the Union, including in the energy sector, and at global level (EC 2020). According to the Union's greenhouse gas inventories data, the energy sector is estimated to be responsible for 16% of methane emissions within the Union in 2022, the second highest methane emitting sector after agriculture (EEA 2024). In the energy sector, methane emissions are primarily linked to mining activities, both in active (coal mine methane, CMM) and abandoned mines (abandoned mine methane, AMM). They account for 38% of methane emissions within the energy sector in 2022, but the situation varies greatly among the EU countries (EEA 2024). For instance, methane emissions from mining activities account for 0% to 4% in France and Belgium since all coal mines were closed at least 20 years ago, while they account for 70% in Poland due to ongoing mining activity.

In this context, the European Parliament and the Council adopted a new regulation on the reduction of methane emissions in the energy sector (EU) 2024/1787, including those from abandoned underground coal and lignite mines (EC 2024). According to the Regulation (EU) 2024/1787 Member States shall:

- set up and make publicly available an inventory of all closed coal mines and abandoned underground coal mines in their territory;
- measure methane emissions in all closed and abandoned underground coal mines where operations have ceased since August 3rd, 1954, and
- designate one or more competent authorities responsible for monitoring and enforcing the application of this regulation in each state.

Finally, the regulation requests the coal mining companies and the authorities to create and implement an emission reduction plan to tackle methane emissions from abandoned underground coal mines that ceased operations after 3rd August 1954.

The new regulation raises two main challenges regarding its implementation without providing any standard or technical guidance. The first one concerns the methodology to carry out the inventory at such a large scale with the need to deal with archives and historical and incomplete data for ancient, abandoned mines. Indeed, the feedback from US inventories carried out by the U.S. Environmental Protection Agency (EPA) highlights the lack of data for mines closed before 1972 and the difficulties to develop methods to assess methane emissions from abandoned mines (US EPA 2004a, 2004b). The situation is probably worse in Europe due to the different regulations and mining situations in the respective countries. Hence this diversity raises questions about how to deal with different mining data reporting systems, which may not have the same reported data. Furthermore, the challenge is likely to increase as the number of abandoned mines is likely to increase, especially in countries with ongoing mining activity such as Poland, and therefore their share in the methane emissions will increase, too (Kholod *et al.* 2020).

The second challenge concerns the emission threshold of 0.5 $t_{CH4}$/a adopted and the obligation to continuously acquire and collect data at each mining emitting component for more than 90% of the period for which it is used to monitor the emissions. The low value of the threshold raises questions about the sensitivity of the current methane and flow sensors. For instance, according to the review of the Yale Carbon Containment Lab carried out in 2022, aerial methane measurement technologies (e.g. UAV, manned aircraft, satellites) currently are not likely to reach such levels of sensitivity although they allow to quickly investigate large areas (Yale Carbon Containment Lab 2022). State-of-the-art UAV technology currently allows to estimate $CH_4$ flux down to ca. 1 g/s (Shaw *et al.* 2021) while the EU threshold of 0.5 $t_{CH4}$/a corresponds to a flux of 0.02 g/s. However, Hollenbeck *et al.* (2021) mention the existence of a small unmanned aircraft system (sUAS) with a minimum detection limit of 0.06 g/s and the existence of a hyperspectral camera that was found to measure flux down to 0.006 ± 0.0006 g/s (23 ± 2.3 g/h) and that can potentially be mounted to an aerial platform. Moreover, large diversity of emissive component configuration, depending on the seal quality, function of its aging and its sealing procedure (Foreman 2016), and the type of component (e.g. shafts, galleries, tunnels), is expected to be encountered. Hence, different methods to measure $CH_4$ flux must be used or developed if they do not exist. Furthermore, $CH_4$ fugitive emissions are known to vary greatly depending on atmospheric pressure (Fleming *et al.* 2021; Hatch *et al.* 2018; Mønster *et al.* 2019; Nambiar *et al.* 2020); hence aggregation methods must also be developed to obtain a single value for the $CH_4$ flux for each component that is representative of the temporal variations.

## Techniques for handling methane

In the past, technologies for extracting and reducing methane degassing in active coal mining primarily served the purpose of keeping the methane concentration in the mine air below the explosive range (4.5 vol. % to 16 vol. %). Depending on local safety regulations, this upper limit is 1 vol. % to 2 vol. %.

Provided suitable measures of explosion protection are applied, mine gas can be used as fuel in gas turbine plants or combined heat and power (CHP) plants to generate energy. To burn methane at concentrations of less than 3 vol. %, energy must be added to the chemical reaction which is usually done by adding more fuel gas, heat or electric energy. Fuel gas is often generated during gas extraction whereas heat can be generated by the incineration process in the reactor itself; electrically heated reactors can burn lean gas flows of approx. 0.18 vol. % and higher. Above this threshold, the combustion heat of the methane itself can be used to generate energy.

Usually, regenerative thermal oxidation (RTO) reactors are used to burn lean gases. These systems can be operated with up to 1.5 vol. % $CH_4$ because the explosion protection required for higher concentrations in the reactors would be technically too complex. RTOs control the lean gas flowing back and forth between two heat exchangers. The heat exchangers are heated by the combustion heat and preheat the incoming lean gas flow for combustion after the reversal. RTOs for industrial use are offered by various plant manufacturers and are in use worldwide with throughput capacities of over 1.2 million $Nm^3$/h.

The RTO reactors are relatively large because of their valve control system and double heat exchangers. An alternative is the thermal recuperative oxidation (TRO) process; here, the shaft gas flows through the combustion chamber and heat exchanger in a co-current flow. According to the manufacturer, TROs only require around ¼ of the space (and presumably the cost) of an RTO. However, TROs for lean methane gas combustion have only been available as laboratory and pilot plants so far.

## Conclusion

The degassing of methane from abandoned hard coal mines provides a major challenge for climate change as methane is a highly effective greenhouse gas. Since the EU Methane Regulation (EU 2024/1787) came into force, the overarching goal is to control and minimise methane emissions. The controlled mine water rebound is one key factor that has the potential to dramatically influence the release of methane.

After mine closure, the mine water rebound may cause a continuous methane release as gas is pushed upwards to the surface; with continuously increasing mine water levels, however, the mine water floods successively the coal seams, i.e., the source of the methane. With each flooded seam the mine water seals the methane inside the coal seam as soon as the hydrostatic pressure exceeds the gas pressure. The process of flooding will diminish the degassing dramatically and finally methane emissions will stop completely.

An essential factor needed here is integrated monitoring which considers the hydrological and geochemical conditions and helps to understand and purposefully control the processes at work. The combination of mine water measurements, gas concentration and isotope analyses and geological data collection enable us to forecast dynamics of methane degassing and identify possible migration paths. It is in particular the signature of the gas that provide valuable information on the origin of the methane and possible extraction processes.

Furthermore, the active control of the mine water rebound provides the opportunity of targeted methane regulation. In conjunction with thermal or energy procedures, measures such as the use of gas extraction systems which are also suitable for low methane concentrations can ensure an effective reduction of methane.

Earlier technologies for methane reduction in coal mining were primarily used for safety reasons by keeping the methane concentration below the explosive range. Today, mine gas can be used to generate energy. Thermal oxidation processes such as RTO or TRO can be used to efficiently burn even lean methane gas.

To summarise: a mine water rebound does not only provide a natural barrier against methane emissions; it also offers technical methods of emission control. Optimising the mine water management and combining it with innovative monitoring and reduction technologies is a promising tool not only to meet the requirements of the EU Methane Regulation but to actively contribute to the fight against climate change.

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