DD-MET

RFCS Research Project

Advanced methane drainage strategy
employing underground directional drilling technology
for major risk prevention and greenhouse gases emission mitigation

BEST PRACTICE GUIDELINES

for methane drainage with Long Reach Directionally Drilled (LRDD) boreholes based on results from the DD-MET project

Co-funded by
the European Union

Research Fund
for Coal & Steel

ACKNOWLEDGEMENTS

This work was carried out by the DD-MET project, co-funded by the European Union via the Research Fund for Coal and Steel, under Grant Agreement No 847338. Additionally, support was provided by the Ministry of Science and Higher Education, Poland, under grant numbers 5073/FBWiS/19/2020/2 and 5038/FBWiS/2019/2.

The study was reviewed and edited by the Coordinator of the project Dr Eng. Grzegorz Leśniak, from the Oil and Gas Institute - National Research Institute in Krakow, MSc Eng. Bartłomiej Jura from the Central Mining Institute - National Research Institute in Katowice, Dr Eng. Grzegorz Plonka, from PGG S.A., and Prof. Dr Sevket Durucan from Imperial College London.

Significant contributions to the study were provided by Prof. Dr Eng. Alicja Krzemień, Dr Eng. Jacek Skiba, Dr Anna Śliwińska, Dr Eng. Piotr Krawczyk, Dr Eng. Arnold Przystolik, and Dr Eng. Nguyen Phu Minh Vuong from the Central Mining Institute - National Research Institute in Katowice; Prof. Dr Eng. Pedro Riesgo Fernández from the School of Mining, Energy, and Materials Engineering of Oviedo; Dr Tomasz Topór, Dr Eng. Małgorzata Słota-Valim, Dr Eng. Wiesław Szott, Dr Eng. Renata Cicha-Szot from the Oil and Gas Institute – National Research Institute in Kraków, and MSc Eng. Dan Brunner from REI Drilling Inc.

DISCLAIMER

The information and photographs in these guidelines remain the property of the DD-MET project or its Partners. Views and opinions expressed are those of the DD-MET project or its Partners only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible.

Executive Summary for Politicians

Methane, a potent greenhouse gas with a greater short-term impact than CO2, significantly affects the atmosphere and alters our planet's climate. The urgent reduction of methane emissions is critical for improving air quality and mitigating climate change, the defining challenge for our generation. This necessity bears not only environmental significance but also presents economically viable opportunities. Considering methane's status as a valuable energy source, it holds the potential to aid local communities in managing the coal phase-out, a process delayed by the energy crisis in 2022.

Meeting the EU regulations restricting methane emissions in the energy sector poses significant challenges for the mining industry. These challenges encompass the organizational, technical, and economic aspects of coal mines. In this context, a meticulously planned methane drainage strategy becomes crucial. Beyond ensuring the safety of miners, it emerges as a pivotal component with far-reaching environmental, societal, and economic implications.

Considering that the energy transition necessitates a measured and sustained approach, akin to a marathon rather than a sprint, the initiatives aimed at phasing out coal mining should be underpinned by a comprehensive, long-term strategy. This strategic framework should incorporate a plan for methane capture not only during the active mining phase but also well into the extended post-closure period of the mines. This approach is essential for effectively managing emissions from decommissioned mining operations.

The results of the DD-MET project, employing Long Reach Directional Boreholes (LRDB) technology, highlight:

- Technology optimization: Comprehensive numerical modelling is an effective tool to optimize the technology by the selection of its most effective operational parameters, such as trajectories of the LRDD boreholes
- Increased Methane Production: LRDB boreholes yielded over twice the methane volume compared to the Cross-Measure (CM) boreholes.
- Enhanced Methane Quality: LRDB boreholes produced higher-quality methane (82%) compared to CM boreholes (30%).
- Optimal Placement for LRDB Boreholes: Boreholes positioned 20-35m above the coal seam in overlying strata proved most effective for methane drainage.
- Efficient Combined System: Combining CM and LRDB boreholes achieved a capture efficiency exceeding 50%, reducing methane concentrations at the longwall face.
- Post-Mining Benefits: LRDB boreholes, active post-mining, benefit adjacent longwall panels, enhancing mine safety and reducing methane emissions.
- Capturing methane at the longface reduces the methane content in ventilation air, leading to a reduction in fees for methane emissions into the atmosphere.

These key findings underscore the effectiveness of LRDB boreholes in increasing methane capture, improving mine safety, and reducing environmental impact, providing valuable insights for policymakers.

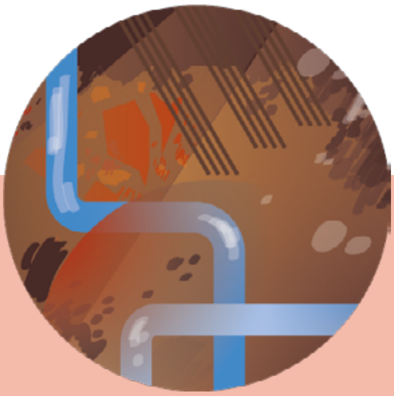


TABLE OF CONTENTS

1. INTRODUCTION

1.1. The challenges of coal mine methane (CMM) in Polish Coal Mines

Methane contained in hard coal seams and partially in the surrounding carboniferous rock mass, due to exploitation and disturbance of gas balance, is released into the environment of mine workings, from where it is removed through ventilation and methane drainage systems. Methane is a product of the coalification process, which poses specific difficulties due to the threats posed by its release into mining excavations. Captured by methane drainage systems for decades, it has also been a source of relatively cheap energy.

Methane emitted into the atmosphere has a very high greenhouse potential. Over 100 years, this potential is 28 times greater than the greenhouse potential of carbon dioxide; over 20 years, it is 86 times greater. In 2022, global methane emissions into the atmosphere reached approximately 630 million kt, of which anthropogenic emissions were about 350 million kt. In 2022, Poland was responsible for roughly 0.5% of global anthropogenic emissions, of which the mining sector was approximately 0.1%. In 2022, hard coal mines emitted about 420 kt of methane. Despite the ongoing restructuring of the coal industry, with fewer mines operating, the emissions and risks are increasing.

Methane, in addition to its unfavorable impact on the environment, is primarily a dangerous, flammable, and explosive gas, responsible for a number of mining accidents and disasters in the last two decades of the 21st century. The need to conduct safe operations and tighten safety criteria for methane have resulted in increased captured methane in recent years, limiting its unfavorable emissions into the atmosphere.

An additional challenge for the mining sector will also be the EU regulations regarding limiting methane emissions into the environment from the energy sector. Ecently, EU set methane emission standards into the atmosphere from methane drainage stations and ventilation shafts to an extremely low level. These will require a much more effective approach to methane drainage and management than before. Meeting the proposed methane emission requirements will pose significant challenges for coal mines in the organizational, technical, and economic spheres. These challenges constitute both an opportunity to develop techniques for obtaining methane and its use and a barrier for the mining industry. The barrier is the proposed emission standards, which, depending on the adopted model - the general approach of the Council (a total ban on the emission or flaring of methane from methane drainage stations and a limit on ventilation emissions from mines of up to 0.5 t of methane per kt of extracted coal) or, according to the relaxed form of the European Parliament, allowing the combustion of unused methane in flares and the ventilation emission limit of initially 5 t and from 2031 3 t of methane per kt of extracted coal, which will be difficult without increasing the efficiency of methane capture and the development of VAM technology to fill. Globally, the efficiency of methane capture using methane removal systems by the mining sector is around 35-40%, while some mines may achieve up to 50-55% depending on the methane drainage systems used. Increasing the efficiency of methane removal and the amount of captured methane encounters technological and economic barriers with classical methane removal methods, increasing production costs. The cost of capturing 1 m^3 of methane ranges from approximately EUR 3 to EUR 8, depending on the quantity and drilling costs.

The development and availability of directional drilling create an opportunity to increase the amount of methane captured and reduce the costs of its capture. Therefore, developing methane drainage techniques based on Long Reach Directionally Drilled (LRDD) boreholes has a very high potential. Current practice shows that the use of LRDD boreholes allows for reducing the scope of the use of classic drainage boreholes or increasing the amount of methane captured by up to 30% with a significant increase in the concentration of captured methane gas up to 98% and on average 80% compared to the usually achieved concentration of 45-60%. At the same time, such a borehole behaves similarly to drainage galleries, being a miniature representation of it.

To summarise, the challenges and opportunities associated with alternative methods, using LRDD boreholes is an extension and complementary approach to the classical techniques. The coal mining industry has specific hopes for such wells related to:

- Obtaining more significant amounts and concentrations of total methane capture;
- Reducing the labour intensity of drilling

drainage boreholes (on average, approx. 2.0-2.6 km of borehole is drilled for every 100 m of the longwall run);

- Reducing the costs of methane capture;
- Reducing methane concentration in workplaces
- Increasing mining efficiency and safety.

Therefore, two main opportunities arise from the above, i.e., safety and increased efficiency. The increased gas concentration obtained through LRDD boreholes should facilitate methane drainage by allowing gas capture with higher efficiency. This will translate into reduced methane release into the working faces while maintaining an appropriately high concentration at the methane drainage station. The project results indicate some solutions, but there is still a need to refine LRDD design in the conditions of coal deposits in the Upper Silesian Coal Basin.

The results of the DD-MET project indicate the great potential of LRDD boreholes in the field of methane drainage. The use of LRDD boreholes will, therefore, probably allow for an increase in the amount of methane captured by methane drainage systems, achieving the two primary objectives described above, i.e., increasing the safety of mining works due to the reduction of methane emissions into mining excavations as a result of increased methane capture and reducing the negative impact of methane on the environment due to lower ventilation emissions of methane. Improving methane drainage systems based on, among others, the widespread use of LRDD boreholes for methane drainage should increase the efficiency of methane capture on a global scale by mining companies to approximately 50%.

The complex character of the DD-MET project required building an interdisciplinary team of geologists, mining engineers, modellers, drilling experts, and experts from risks, life-cycle, eco-efficiency, and economic analysis. The project was carried out by professionals from scientific community such as Oil and Gas Institute – National Research Institute (INiG-PIB), Central Mining Institute – National Research Institute (GIG-PIB), Universidad de Oviedo (UNIOVI), Imperial College London (IMPERIAL), and coal mining industry representatives such as Polska Grupa Górnicza (PGG), and the REI Drilling (external consultant).

1.2. The target group for these guidelines

The Best Practice Guidelines for methane drainage with LRDD boreholes play an essential role in addressing a critical aspect of accessing deep gassy coal seams. Recommended principles and standards, derived from case studies, can furnish decision-makers with a solid foundation of understanding to guide policy and commercial decisions.

Such knowledge is critical for achieving an extended gas drainage range, ensuring operational continuity, realising cost savings, and enhancing safety of miners.

This document aims to supplement current technical resources by offering accessible, high-level guidance to mining engineers, scientific comunity supporting the proces of developing a comprehensive coal mining projects, senior corporate, government, and financial decision-makers. These key stakeholders all play pivotal roles in determining the implementation of best practices.

The guidelines document can serve also as an introduction to essential methane management principles and references for both students and technical specialists

The Best Practice Guidelines does not override or take precedence over laws, regulations, or other legally binding instruments, whether at the national or international level. The principles detailed in this document are designed to offer supplementary guidance, enhancing existing methane drainage technologies, and promoting the development of safer and more efficient practices as industry standards and regulations evolve. While its primary objective is to support performance and suggest a potential approach for initiating the development of a methane drainage system, one that can have a positive effect on climate and greenhouse gas emissions while also contributing to the societal aspects of energy transition.

2. THE FIELD SITE OF INVESTIGATION

2.1. Geological description

The study area within the DD-MET project was located within the multi-seam Staszic-Wujek Coal Mine in the central part of the Upper Silesian Coal Basin (USCB) in southern Poland (Fig.2.1A). The USCB is situated in the Upper Silesian Block, the northeastern part of the Brunovistulicum terrane (Kotas 1985; Buła et al. 1997; Buła and Żaba 2008; Nawrocki and Poprawa 2006; Buła et al. 2015). The productive carboniferous complex in the Staszic-Wujek Coal Mine consists of the Pennsylvanian strata, within which the following parts can be distinguished: Cracow Sandstone series, Upper Mudstone series, Upper Silesian Sandstone series, and Paralic series.

The zone of particular interest in this study is the Upper Silesian Sandstone series developed as poorly sorted sandstones interbedded with shales and mudstones with coal seams belonging to the Rudzkie beds, deposited below coals seam 407 and between coal seams 501 and 510 belonging to the Siodłowe beds (Fig.2.1.1B) (Stankiewicz 1955; Hanzlik 1963; Dembowski et al. 1964; Kotas and Malczyk 1972; Dembowski 1972). The I-C and II-C longwalls panels were developed in coal seam 501, which belongs to the Siodłowe Beds of the Upper Silesian Sandstone Series. The coal seam 501 was deposited at depths of approximately 550–590 m below sea level in the study area and gently dipped towards the SW direction. This trend is maintained in the C field panel, limited by the fault system consisting of the Książęcy fault, the Kostuchna fault, the Murckowski fault, and the Jakub fault (Fig. 2.1.1). The thickness of the coal seam 501 in the study area varies between 0.6 and 4.5 m (Fig. 2.1.1 C and D). The location of the study area is shown in Fig. 2.1.1.

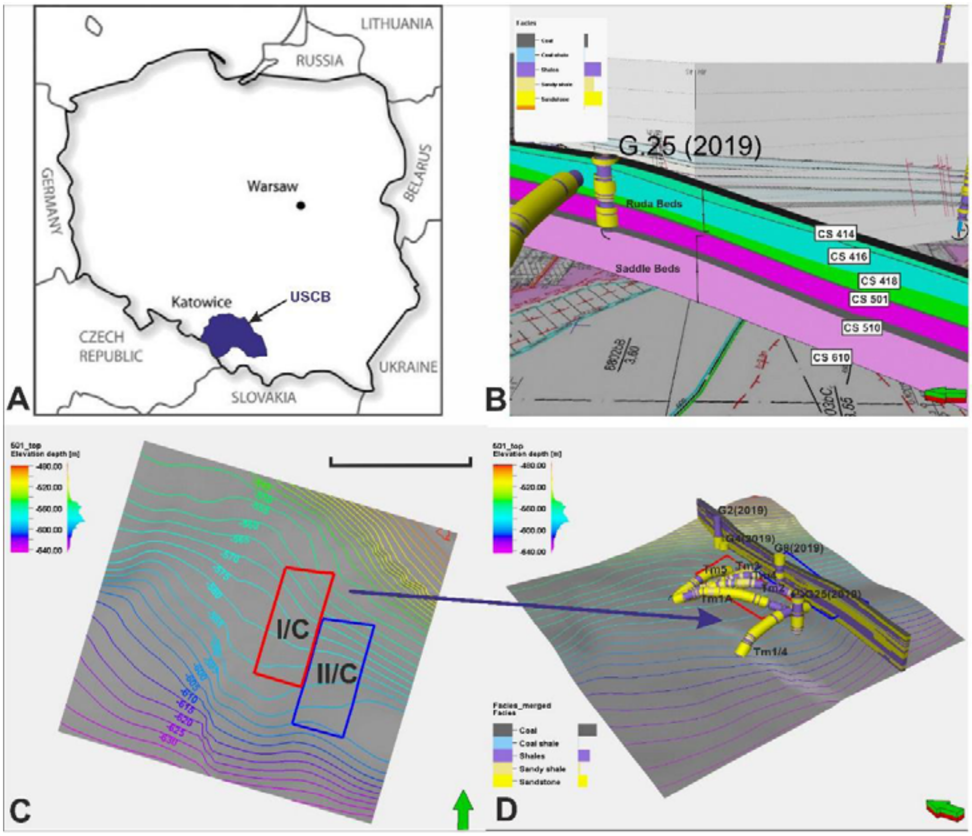


Fig. 2.1.1. Location of the study area: the Upper Silesian Coal Basin in Poland (A), Cross-section through the interval of drainage (B), position of I-C and II-C longwalls (C), cross-section of the lithotype model in the vicinity of the I-C and II-C longwall panels (D).

2.2. Sources of CMM emissions

Methane emissions into mine workings mainly come from the mined coal seam and its neighboring rock layers (Lunarzewski and Battino 1983; Prusek 2020). It depends on the progress of the longwall and the associated disturbance of the rock mass structure, which causes methane desorption from neighboring coal seams and the outflow of free methane from macropores and sandstone fissures.

Longwall I-C was exploited in the KWK Staszic-Wujek Coal Mine at 550-590 m below sea level in the coal seam 501. The panels I-C and II-C were excavated with a crosswise roof collapse system. Longwall I-C had the following technical parameters: coal panel height – up to 3.7 m, coal panel width: 159-161 m, longwall panel length – 400 m, max. Longwall II-C had coal panel height – up to 3.4 m, coal panel width: 160 m, and longwall panel length of 465 m.

In the roof of coal seam 501, sandstones with a thickness of up to 13.0 m occur in most of the area of the coal panel, while claystones/mudstones with a thickness of up to 2.0 m occur in the southeastern part of the wall. At the bottom of coal seam 501, there are claystones/mudstones with a thickness of 6.10 to 9.50 m and sandstones below them. There are also other coal seams, such as seam 416 at a distance of approx. 51.0 m above seam 501 and seam 510 approx. 34.50 m below the seam 501 (Fig. 2.1.1B). The disturbance of the rock mass in the area of mining is relatively small. Even though the methane content of the coal seam, in the area of the preparatory works carried out in the coal seam 501 has been classified as the highest IV category methane hazard according to Polish regulations. Fig. 2.2.1 shows the isolines of methane content in the coal seam 501.

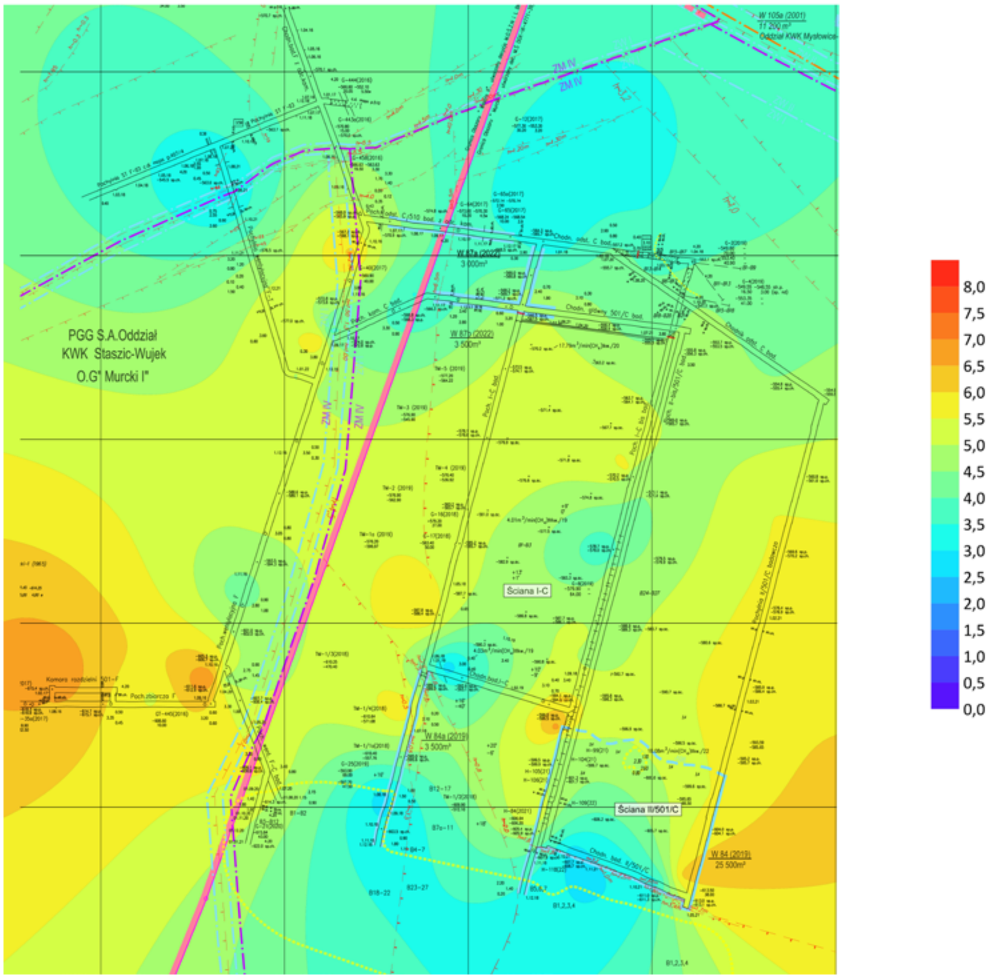


Fig. 2.2.1. Isolines of methane content in the coal seam 501 and the I-C and II-C longwall panels.

3. METHANE CONTROL STRATEGY IN STASZIC-WUJEK COAL MINE

3.1. Design considerations for methane drainage

Methane drainage systems for active longwalls must be designed to ensure safe working conditions at the planned longwall face advance rates. The key is to control methane emissions from the cutting face and from the disturbed overlying and underlying strata, and th goaf, through dilution with ventilation and through collection by methane drainage systems.

In Polish mines, methane emissions from active longwalls typically cannot be controlled by ventilation alone and methane capture is essential to maintaining permissible methane gas concentrations in the ventilation air courses - along the longwall face, at the intersection of the longwall face and the tailgate entry, and along the tailgate entry, and through the return entries. A key parameter in methane drainage is the efficiency of capture which is the volume of methane captured divided by the total volume of methane liberated by the active longwall and the surrounding source seams (ventilation plus capture).

Some systems of active longwall drainage have a better capture efficiency than others, while some have a high capture efficiency but recover gas at lower methane concentrations (methane and ventilation air mixture) than others. Ideally, an active longwall drainage system that operates at a high capture efficiency and recovers methane gas at high methane concentrations is preferred. The amount of methane emissions anticipated from an active longwall panel determines the selection of the ventilation system and airflow quantities, and the methane drainage system.

Factors that affect methane emissions from active longwalls are (i) the rate of longwall mining face advance and the cutting height, (ii) the in-situ methane content of the mined, and and underlying coal seams (or other surrounding gas producing source rocks), (iii) the proximity of overlying and underlying gas source seams relative to the mining seam, (iv) the in-situ permeability of the overlying and underlying source seams and adjacent strata, and the effective permeability of these formations when under and over-mined, (iv) the form and extent of the goaf area which depends on the geo-mechanical characteristics of the overlying and underlying strata, depth of cover, panel geometry, adjacent mining, stresses, and mining height, among a number of other considerations, and finally (v) the amount of pre-mine drainage performed in advance of longwall mining with in-seam boreholes, vertical frac wells, laterals drilled from the surface, and the impact of adjacent mining to gas content reduction.

The following methane drainage methods are currently used for active longwalls and are depicted generally in Fig. 3.1.1:

- Sets of single or multiple boreholes drilled at angles up across the measures (cross-measure boreholes – CM boreholes) and towards the advancing face from the tailgate entry (or low pressure return air course), and in some cases from both sides of the panel (headgate and tailgate entries) (Fig. 3.1.1 - a);
- Vertical goaf wells developed from surface or intermediate mining levels, completed to above the coal seam and placed between mid-panel and the tailgate entry (or low pressure return air course) (Fig. 3.1.1 - b);
- Overlying drainage galleries, typically developed above and longitudinally along the longwall panel in coal or in rock as part of longwall panel developments (Fig. 3.1.1 - c);
- Overlying drainage galleries from which drainage boreholes are drilled over the longwall panel in advance of mining (Fig. 3.1.1 - d), or;
- A combination of the methods described above.

And more recently:

- LRDD boreholes drilled in advance of longwall mining, and placed above the mining seam generally perpendicular to or at angles to the longwall panel (Fig. 3.1.1 - e);
- LRDD boreholes drilled above the mining seam and placed along the longitudinal axis of the longwall panel (Fig. 3.1.1 - f), or;
- A combination of LRDD boreholes and CM boreholes.

In all cases, methane drainage methods for active longwalls are only effective when operated under vacuum pressure.

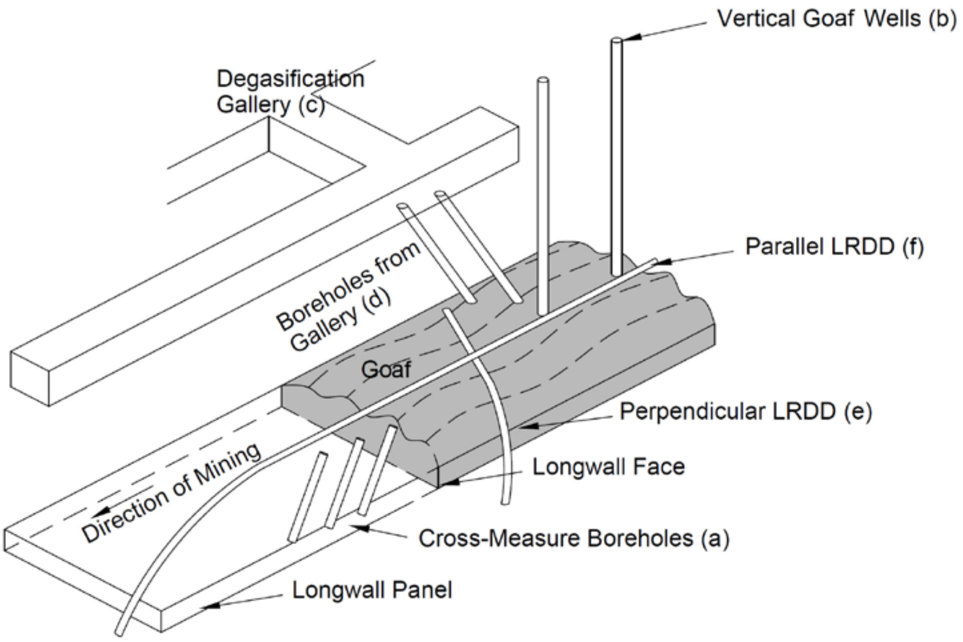


Figure 3.1.1. Methane drainage methods for active longwall panels.

The commonly used active longwall methane drainage strategies listed above have some limitations:

Cross-Measure (CM) Boreholes: Limited production life as the integrity of the borehole collars is affected by stress changes resulting from the oncoming longwall face. This results in the recovery of lower quality gas (average 30% methane in the drained gas by volume at Staszic-Wujek), and management of vacuum at the wellhead to increase methane concentration is difficult because of the number of collars and wellheads. In some cases, collected and transported mixtures of methane and air from CM boreholes may be in the explosive range. This system's drainage efficiency is lower than others (typically 30%).

Vertical Goaf Wells: Typically, high-volume systems recover goaf gas at high methane concentrations suitable for CMM utilisation or combustion. However, the application is subject to surface drilling restrictions and drilling risks through multi-level mining operations and requires monitoring and maintenance of the surface vacuum plant. Typically, multiple vertical goaf wells are required per panel.

Drainage Galleries/Drainage Galleries with Boreholes: High volume systems recovering gas at low to medium methane concentration levels at high drainage efficiencies (up to 60%). These systems are costly; typically, the galleries are mined in rock before longwall panel developments. These systems need to be developed significantly in advance of mining and are not very flexible to changes in mining plans.

While the use of LRDD boreholes for degasification of active longwalls is relatively new in Poland (2015), this system has been applied at mines globally, particularly in Australia, China, and in the USA for more than a decade prior to 2015. The use of LRDD boreholes for the degasification of active longwall panels provides a number of benefits relative to the commonly used methane drainage strategies. These benefits include (i) the ability to strategically place a few boreholes at select elevations above the mining seam to create a continuous low-pressure zone in the goaf reservoir, (ii) the ability to strategically place boreholes laterally in zones of high permeability, (iii) the ability to initiate boreholes from areas that will not be affected by mining-induced stresses, providing for collar integrity and minimising the intrusion of air, (iv) the ability to create a manifold of boreholes from a single wellhead and collar by side-tracking, (v) the ability to easily manage the performance of this system by monitoring and controlling gas flow rate, methane concentration, and wellhead vacuum - from a few wellheads, and (vi) the ability to continue to produce gas long after longwall mining is completed.

Many factors affect the implementation and performance of LRDD boreholes; these include, the geomechanical characteristics of the overlying strata, vertical placement above the mining seam, lateral placement relative to the longwall panel, and borehole diameter and wellhead vacuum pressure, which drive the capacity of the LRDD boreholes.

Geomechanical Characteristics: LRDD boreholes are implemented with directional drilling systems that utilise a water/mud-driven downhole motor (up to 4 l/s). As these boreholes are drilled up into overlying strata from underground, drilling is performed in an under-balanced manner, making it difficult to maintain borehole stability in weaker strata. The lack of annular pressure and the high-water volumes required make directional drilling challenging in broken, friable, or swelling strata. As LRDD boreholes are typically drilled parallel to stratigraphic layers, geologic information of the overlying formations is of importance, and using logging while drilling system (focused gamma, for example) to assist in navigating the LRDD boreholes in competent strata is very beneficial. In all cases, drillers should anticipate weak strata, minimise borehole re-entry, and directionally drill to the ultimate diameter in one drilling pass.

Vertical Placement: LRDD boreholes should be strategically placed in elevation based on the proximity of the lowest producing overlying gas source seam and the height of the waste and fracture zones above the goaf. The elevation should be such that the LRDD boreholes remain intact and produce gas over their entire length when under-mined. Typically, this is 20 to 35 m above the mining seam, depending on the lateral position of the LRDD borehole. If the LRDD boreholes are placed too high in elevation, they are less effective at controlling gas emissions into the longwall's ventilation system due to lower strata permeability. If the LRDD boreholes are placed too low in elevation, they may not remain intact when undermined, produce gas only from the under-mined end of the borehole, and draw in ventilation air depending on longwall face activities.

Lateral Placement: LRDD boreholes should be strategically placed near the margins of the longwall panel where the overlying strata are in tension once the goaf is formed, avoiding the zone of goaf re-compaction along the centerline of the panel. Ideally, LRDD boreholes should be developed along the longitudinal axis of the longwall panel (parallel versus perpendicular), away from the center line, and along the low-pressure side of the longwall panel adjacent to the ventilation return air course.

Diameter and Wellhead Vacuum: LRDD borehole capacity is dictated by borehole length, diameter, and wellhead vacuum. Shorter, larger diameter LRDD boreholes operated under high wellhead vacuum will produce higher gas volumes.

3.2. The role of geological modelling in CMM exploitation

Numerical modelling of geological structures and computer simulations of various processes is essential to understanding geomechanical and gas flow behaviour of these structures when undermined by a longwall face. They include coal seams and their geological environment. In particular, natural processes occurring during coal mining can be better understood and predicted using highly accurate numerical methods employed in computer simulations performed on appropriate numerical models. Specific problems concerning coal mining include methane drainage for safety measures and concomitant methane recovery as a valuable asset of coal mining. This numerical modelling approach and computer simulations were applied to analyse the advanced methane drainage strategy employing underground LRDD boreholes technology and assess their effectiveness in the Staszic-Wujek Coal Mine.

The main lesson learned from the study proves the significance of coupled geomechanical and flow simulations in the quantitative assessment of the strategy. This approach includes several components described below and illustrated in Fig. 3.2.1.

1 Obtaining complete characterisation of the coal seam under consideration, including geological and geomechanical parameters of the seam and its surroundings. The most significant parameters include:

  A parameters determining the reserves of methane adsorbed in the coal matrix, the degree of its desorption for a given drainage pressure (parameters of the adsorption isotherm), and diffusion transport properties of the coal matrix,

  B geomechanical parameters of the coal matrix as well as the surrounding clastic rocks to assess stress and strain distributions and their dependents on pressure variations during the seam excavation process,

  C correlations between modified geomechanical state and transport properties of the coal and clastic rocks.

2 Construction of geological, geomechanical, and dynamical models of the studied coal seam and its surroundings. The models should be constructed as digital representations of subsurface multicoal-seam and interbedding formations with their associated features. The following data are typically used: borehole lithological profiles, coal seam structure and thickness maps, cross-sections, and basin-scale tectonic settings. Within the framework of the 3D structural models, parametric models of petrophysical and geomechanical properties are developed based on well-logs and laboratory data, possibly supplemented with literature data and other characteristics of coal and other lithotypes occurring in the modelled area. They included density, porosity, permeability, and elastic and strength properties (Fig. 3.2.1).

3 Developed static parametric models built in the geometry defined by 3D structural models are used to construct a dynamical model. Structural maps of coal seams, cross-section, and lithological profiles in boreholes drilled from the coal seams and the top surface, results of well-log data analysis and distribution of parametric models including 3D models of lithotypes and geomechanical properties for the analysed example of advanced methane drainage employing underground LRDD boreholes technology as shown below.

4 Implementing the proposed LRDD borehole system and other methane drainage systems (ventilation, CM boreholes, etc.) in the coupled dynamic model to simulate changes in stress, fracture, pore pressure, permeability and gas flow patterns during mining following a modelling workflow as illustrated in Fig. 3.2.1 to Fig. 3.2.5.

5 Carrying out coupled geomechanical and flow simulations to assess and compare the performance of LRDD system with that of other commonly used methane drainage techniques.

6 Use of simulation modelling as an effective tool to optimise the technology by the selection of its most effective operational parameters, such as trajectories of the LRDD boreholes.

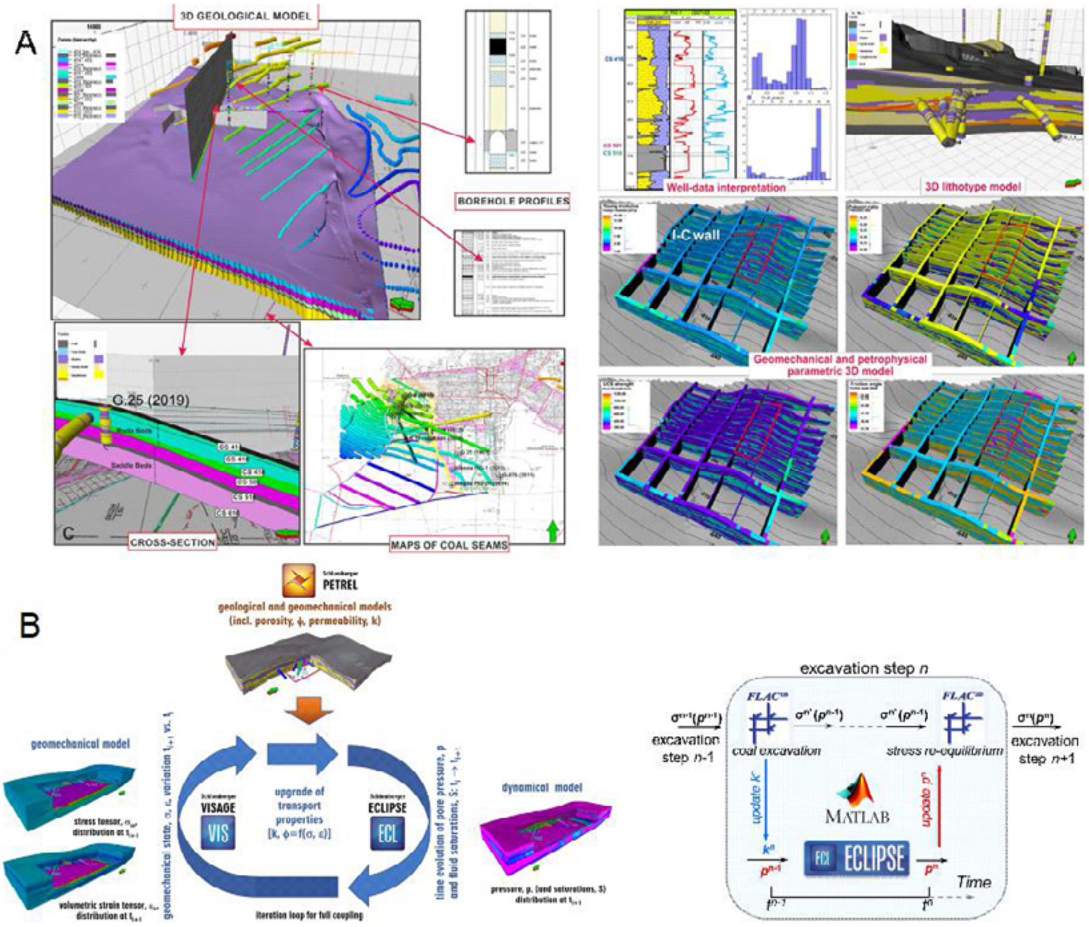


Fig. 3.2.1. 3D structural large-scale model construction of multi-seam coal mine with local scale parametric models in the vicinity of the I-C longwall (A), the two coupled geomechanical and flow simulation workflows used by INiG and IMPERIAL in numerical modelling (B).

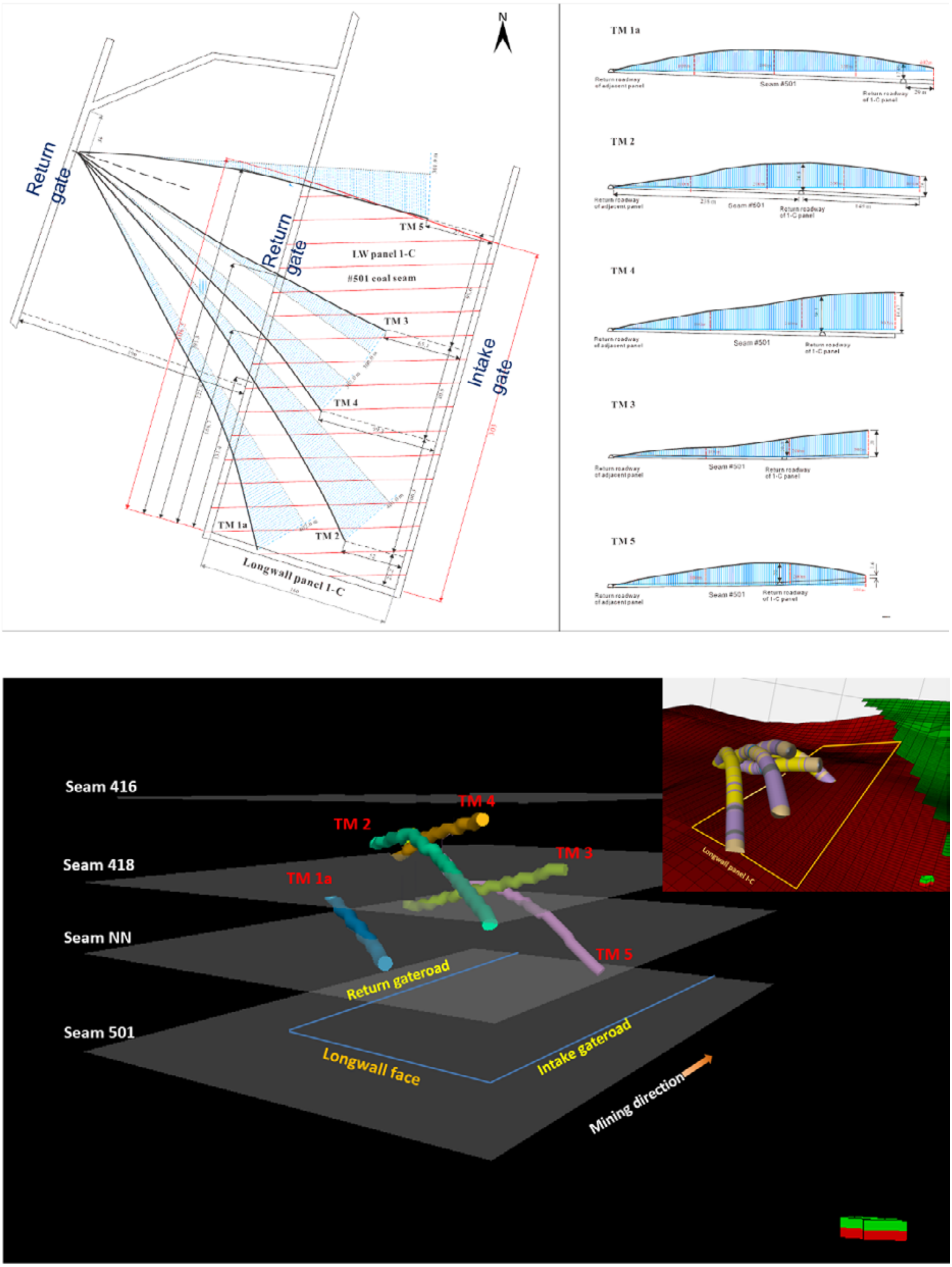


Fig. 3.2.2. Plan view showing longwall panel I-C and the configuration of the LRDD drainage boreholes (A), and modelled strata failure and fracture patterns (B), pore pressure changes (C) and horizontal permeability enhancement around longwall I-C during coal production (D and E).

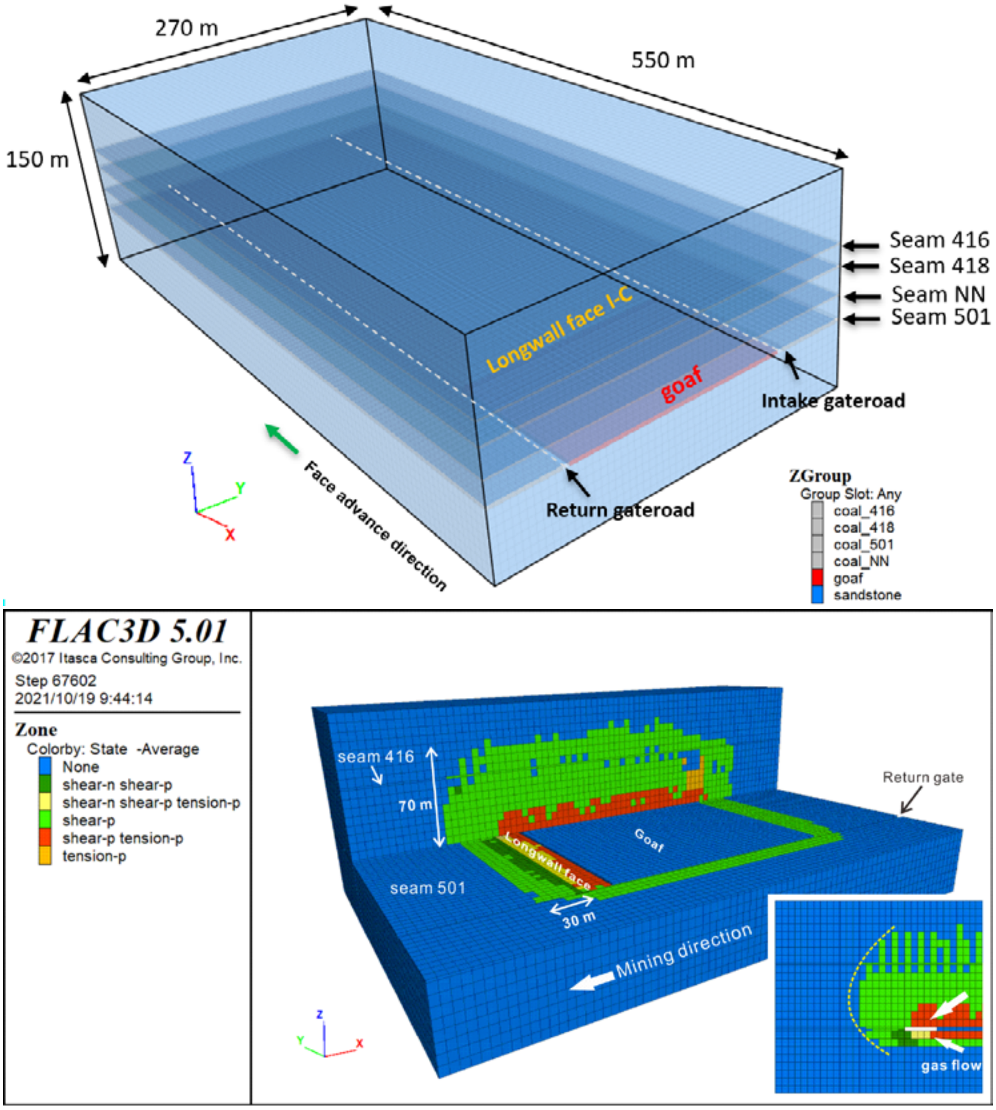


Fig. 3.2.3. Coupled geomechanical and flow model domain with the mined and gas source coal seams and longwall I-C represented (A), failure zone development around longwall face I-C obtained the by the geomechanics model (B).

The reliability of this approach is confirmed by its ability to reproduce historical exploitation data, such as methane production by the ventilation system, as shown below (Fig. 3.2.4).

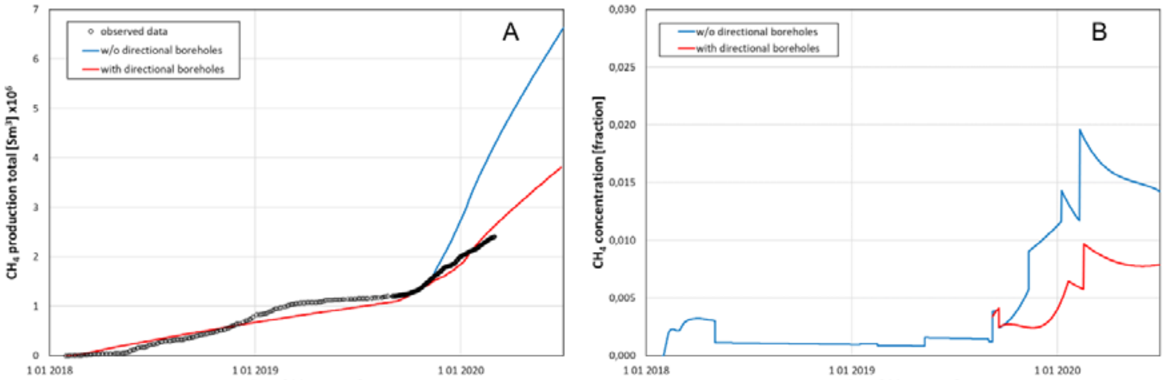


Fig. 3.2.4. (A) Total outflow of methane in the ventilation system: observed data (black circles) vs model results with LRDD boreholes (red curve) and model results without LRDD boreholes (blue curve), (B) Methane concentration in the ventilation system: model results with LRDD boreholes (red curve) and model results without LRDD boreholes (blue curve).

The above results of methane production refer to the analysed example of advanced methane drainage employing underground LRDD borehole technology. The simulation modelling described above allows its operator to assess the effectiveness of the LRDD boreholes technology by comparing methane production by the ventilation system and methane concentration in that system with and without this technology. In particular, applying the LRDD boreholes technology decreases the methane content in the ventilation air by ca. 52%.

This selection depends on the optimisation criterion as the use of the LRDD boreholes technology presents twofold advantages: (i) reduction of methane concentration in the ventilation air and (ii) increased methane production from the coal mine.

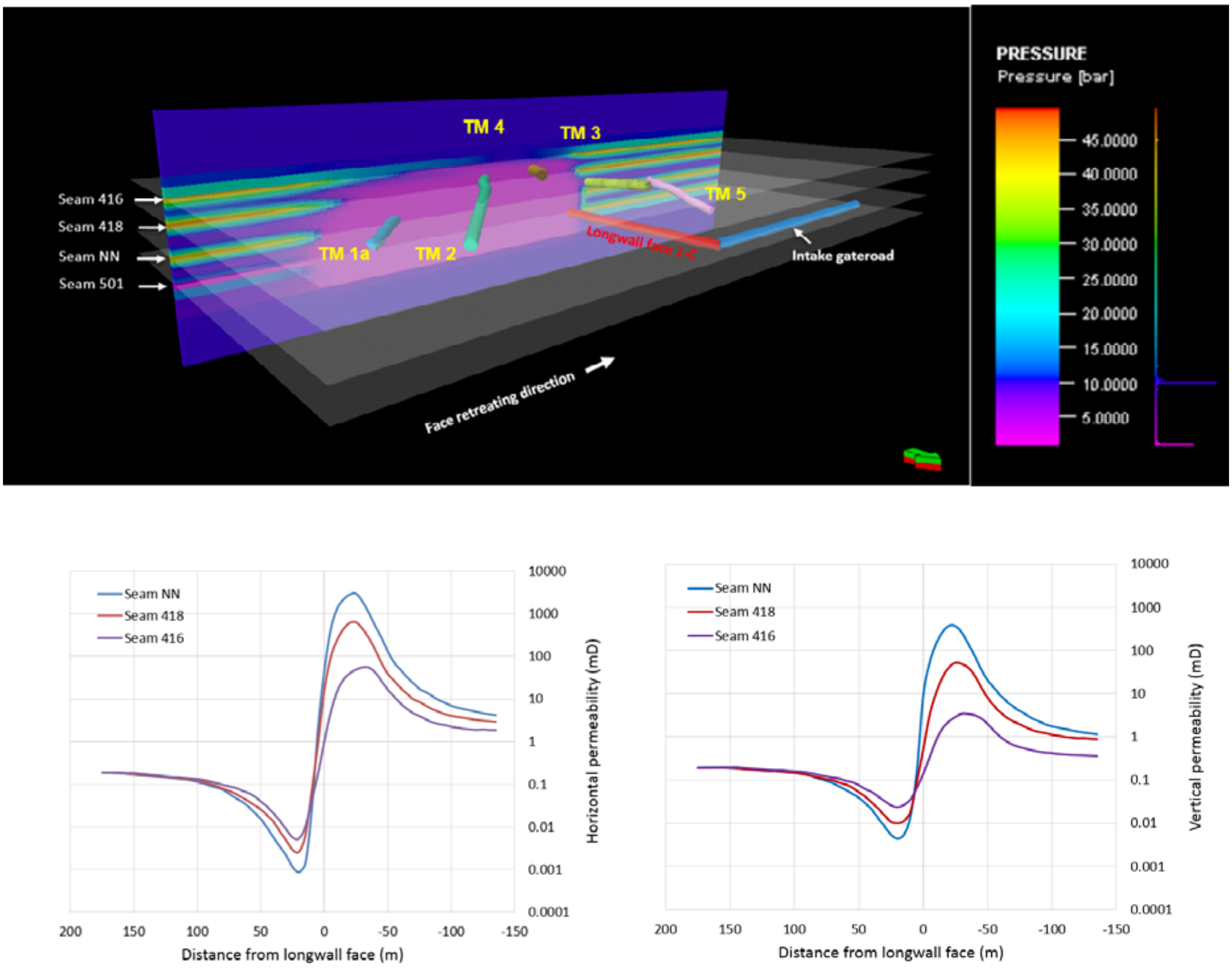


Fig. 3.2.5. Pore pressure changes and enhanced permeability zone development around longwall I-C during coal production (A), enhanced horizontal and vertical permeabilities in gas source seams with respect to horizontal distance from the face line (B and C).

Coupled dynamic simulation of geomechanical and gas flow behaviour of the coal seams and the coal measures rocks around longwall I-C have also revealed that:

- Permeability of the overlying strata above the mined coal seam increases over two orders of magnitude on average, and up to three orders of magnitude in areas close to the production level (Fig.3.2.5A).
- For the same coal horizon, horizontal permeability is around one order of magnitude higher than that of vertical permeability, with the highest permeabilities induced at 25-35 m behind the face line (Fig.3.2.5B and Fig.3.2.5C).
- The LRDD boreholes' output starts to increase when the distance between the face-line and the borehole is around 20 m, reaching peak drainage rates when the face-line passes the corresponding borehole by about 20-30 m.
- Peak drainage rates modelled for the 5 LRDD boreholes varied between 3.9-8.4 m³/min, consistent with the field monitored peak drainage rates,

which were in the range 2.0-7.1 m³/min. The placement horizon of the borehole, its horizontal/vertical distance from the face-line/mining horizon at any time during coal production, and the in-coal-length of the borehole affects peak drainage rates, and when this peak is reached by each borehole. In that respect, borehole TM 2 with the maximum in-coal--length in the seams above achieved the highest gas production rate, whereas borehole TM 4 with a relatively smaller in-coal-length at a relatively larger vertical distance above the production horizon yielded the lowest drainage rate (Fig 3.2.6).

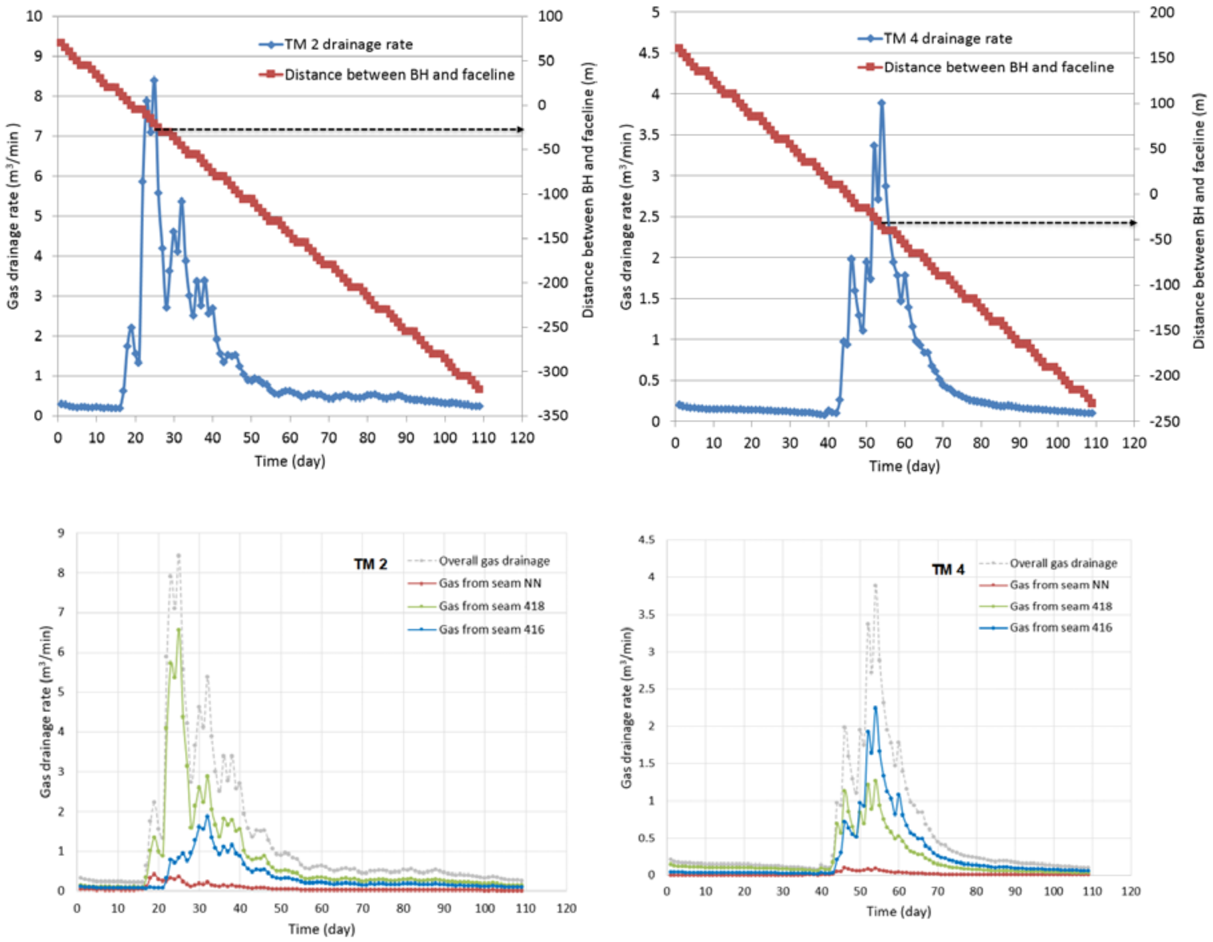


Fig. 3.2.6. Gas drainage rate vs. distance between borehole and face-line (A) and (B), Total gas captured and the respective contributions from each overlying seam for LRDD boreholes TM 2 and TM 4 (C) and (D).

- Maximising the in-seam lengths of LRDD boreholes would capture the maximum volume of methane released from a seam. Placing the maximum possible length of borehole TM 4 in seam 418, which is approximately 30 m above the mined seam 501, was found to achieve 31.5% increase in the cumulative gas drained from that seam (Fig 3.2.7).
- Investigating the effects of borehole spacing on LRDD borehole performance it was found that tightly spaced LRDD boreholes may drain much higher total volumes of methane, which increases drilling cost significantly. On the other hand, drainage performance per metre of borehole drilled increases with wider spacing of boreholes, which eliminates the competition between boreholes (Fig 3.2.9A and Fig 3.2.9B).
- Comparing the performance of LRDD boreholes with that of parallel CM and bundled leapfrog CM boreholes commonly employed in Europe (Fig.3.2.8), the model findings have suggested that: (a) the bundled leapfrog system may yield slightly better total drainage volume than parallel CM borehole layout, but this would be in the expense of significantly increased drilling costs, (b) Overall, in both cumulative gas production and borehole utilisation rate, LRDD boreholes would overperform the two types of CM roof boreholes (Fig 3.2.9C and Fig 3.2.9D).

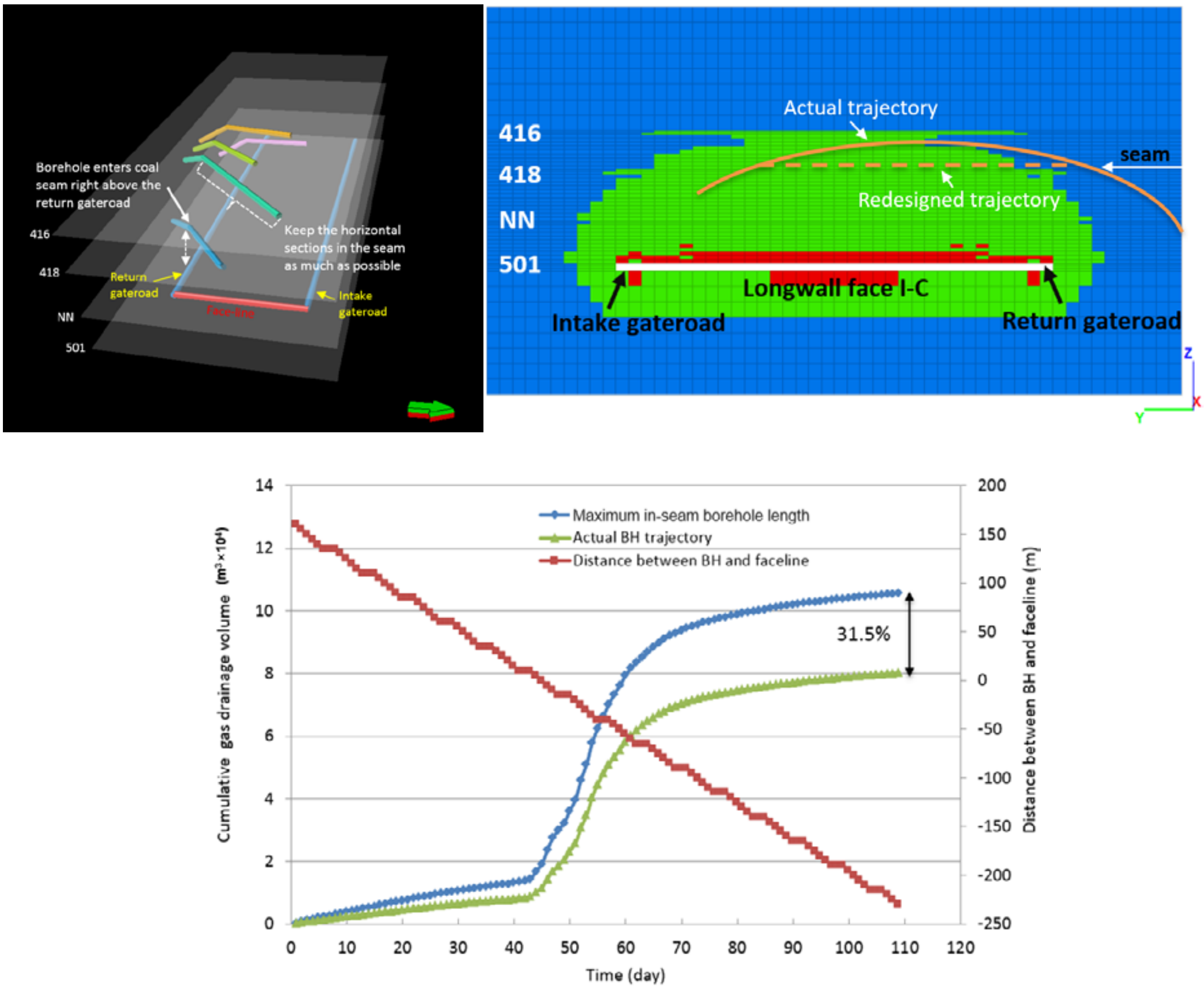


Fig. 3.2.7. Numerical model for maximised in-seam length borehole trajectories with the longest horizontal section within coal seams (A), Schematic illustration of actual and maximised borehole trajectory for LRDD borehole TM 4 (B), Comparison of the cumulative gas drainage volume from the field achieved trajectory and the maximum in-seam trajectory for LRDD TM 4 (C).

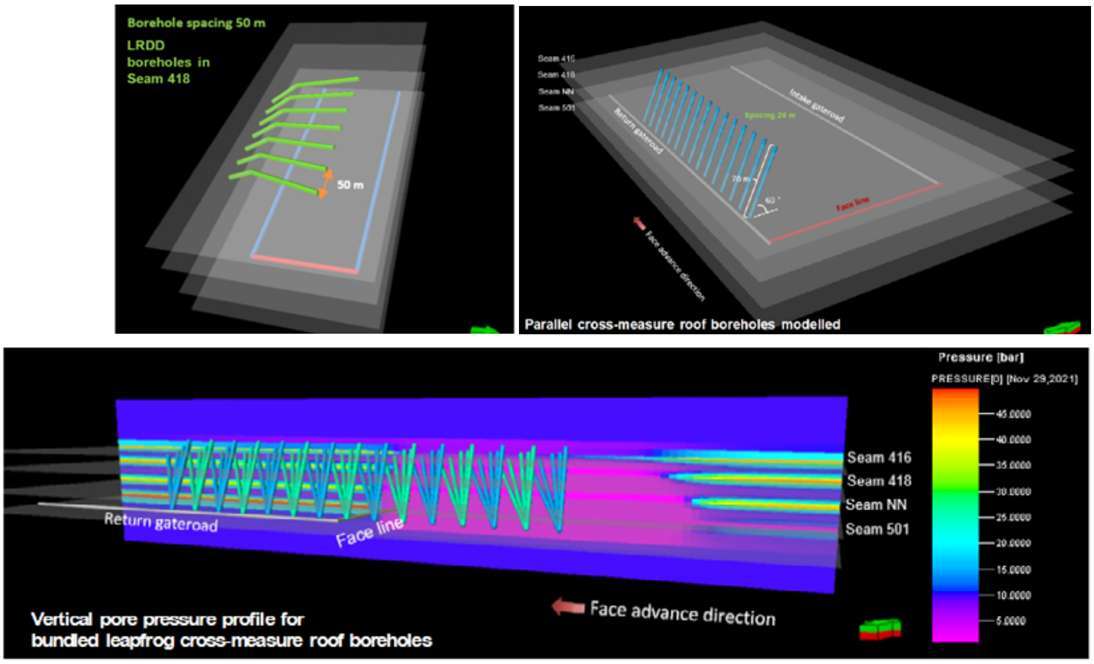


Fig. 3.2.8. Examples of idealised layouts for different drainage borehole designs and borehole spacings (A and B), pore pressure changes modelled for CM boreholes at longwall I-C (C).

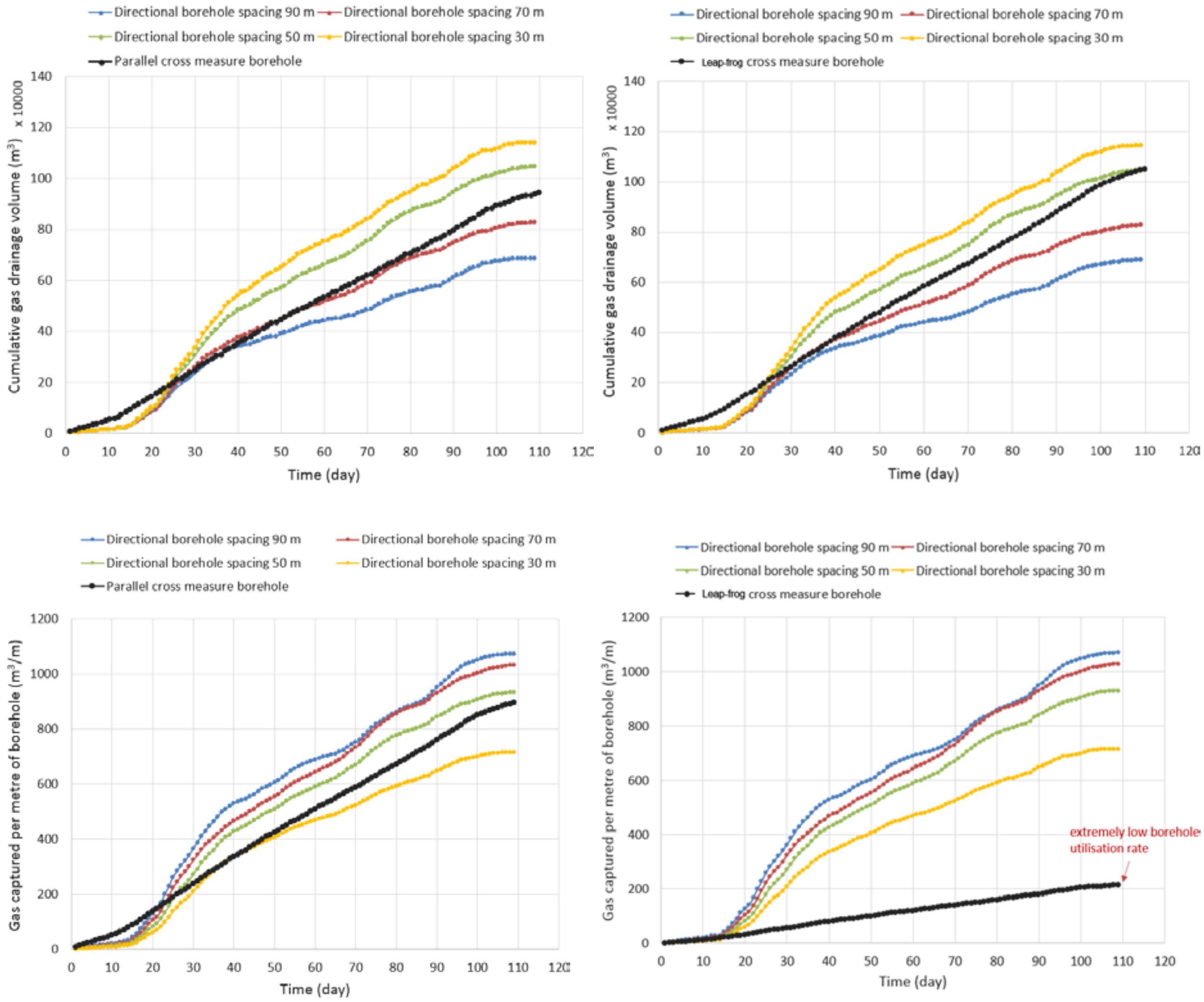


Fig. 3.2.9. Drainage performance comparison for LRDD boreholes, parallel cross-measure and bundled leapfrog CM boreholes. Total gas drainage volume vs. borehole spacing (A and B), and gas captured per metre of borehole (C and D) for the three drainage technologies compared.

3.3. Assessment of methane drainage efficiency with classic and LRDD boreholes systems

At the Staszic-Wujek Coal Mine, longwalls I and II-C exploited the 501 coal seam and were ventilated with a "U" system with air flowing across the longwall face via the intake gate road, and the return air via the return gate road. A combined methane drainage system was used for both longwall panels consisting of LRDD and CM boreholes.

The CM boreholes were installed in an overlapping fashion to maintain a continuous low-pressure zone to control gas emissions and maintain permissible methane limits in the proximity of and outby of the intersection of the longwall face and the return gate road.

In addition to the CM boreholes, two different variants of LRDD boreholes were implemented. Five LRDD boreholes were drilled perpendicular to the I-C longwall panel from a ventilation roadway approximately 190 m west of the longwall panel. The limitation of suitable sites for directional drilling dictated this configuration. For longwall II-C, three LRDD boreholes were drilled parallel to the longitudinal axis of the longwall panel, which is the orientation applied globally.

Although implemented in conjunction with CM boreholes, the effectiveness of the LRDD boreholes was successfully demonstrated. More methane was captured during active longwall mining, and methane concentrations at the longwall face and return gate road intersection were measured at reduced levels. Because the LRDD boreholes could be produced after completion of mining, the LRDD boreholes placed over Longwall I-C provided benefits during longwall mining of the adjacent Longwall II-C because of connectivity across both goaf areas.

Measurements of the methane concentration of the gas recovered from each LRDD borehole suggest that high methane concentrations can be captured with this system. Table 3.4.1 presents the average methane concentration achieved by the individual LRDD boreholes TM1-TM5 for longwall I-C. The average methane concentration of the gas recovered by all five LRDD boreholes was 82%. For the CM boreholes, the average methane concentration was approximately 30% based on measurements obtained from a sample of six sets of CM boreholes (5 boreholes per set) - TM7-TM12, as shown in Figure 3.4.1.

Table 3.4.1 - Average gas production characteristics of the LRDD boreholes for longwall I-C.

	Lenght	**Drained Gas Flowrate**	**Methane Concentration**	**Wellhead Vacuum**
	L (m)	Qavg (m^3/min)	Aavg (%)	Vavg (mm Hg)
TM1a	402	1.8	42	48.4
TM2	401	4.5	88	49.5
TM3	301	4.5	94	58.3
TM4	300	6.2	79	59.7
TM5	302	3.6	83	48.5

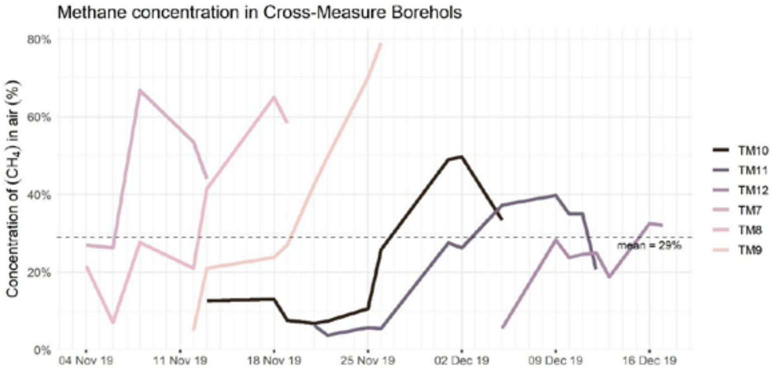


Fig. 3.4.1. Range of methane concentration captured by a sample of sets of CM boreholes implemented on I-C panel.

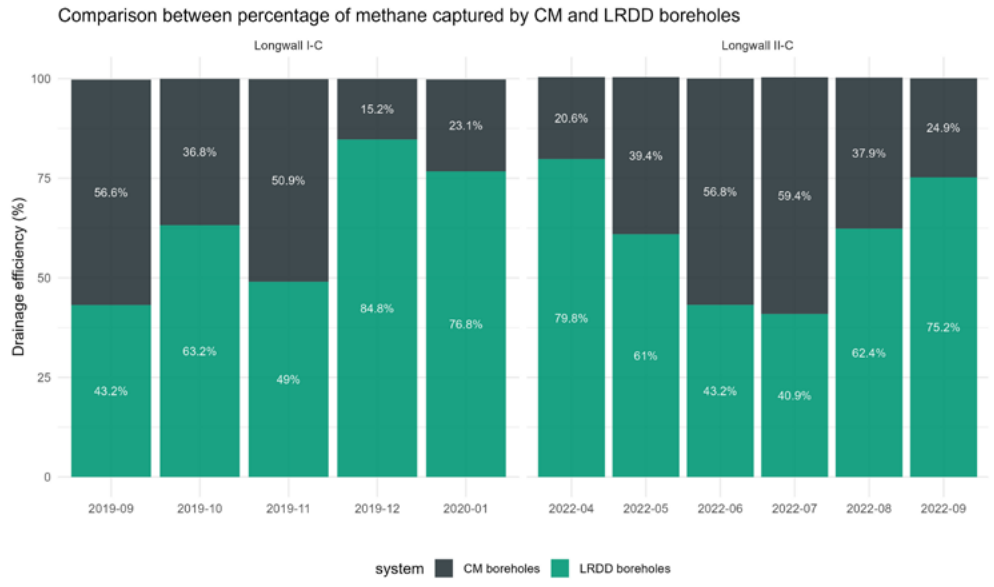


Fig. 3.4.2. Percentage of methane captured by each system per month during mining of longwall I-C (mining (September 2019 – January 2020) and longwall II-C (April – September).

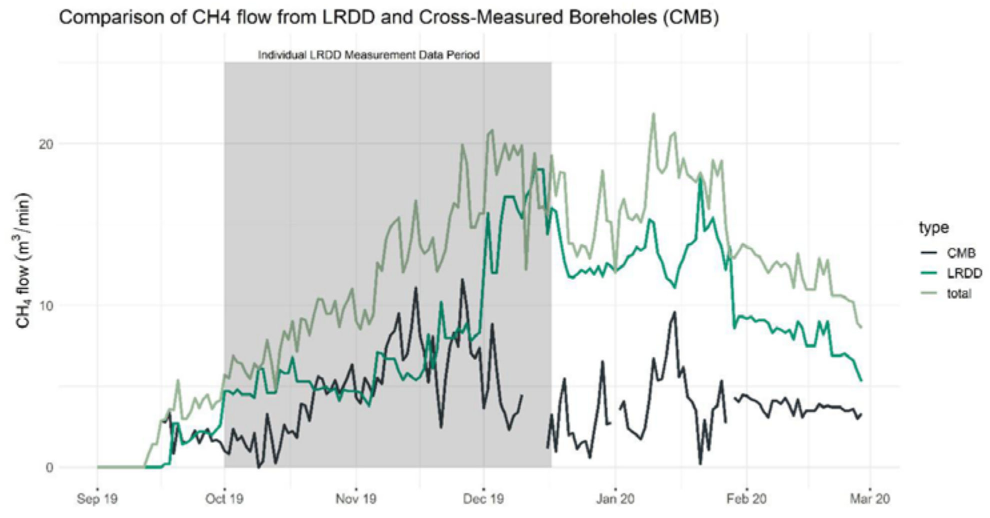


Fig. 3.4.3. Methane volumes produced from cross-measure and LRDD boreholes during mining of Longwall I-C.

As for the total volume of methane recovered by each of the two systems for longwall I-C, the LRDD boreholes recovered 63% of the total methane captured. In contrast, the CM boreholes recovered 37%, as shown in Fig. 3.4.2. The measured methane flow rates for the CM boreholes (average of 3.75 m^3/min) and the LRDD boreholes (average of 8.6 m^3/min) during the mining of longwall I-C are shown in Fig. 3.4.3

During the mining of longwall II-C, the percent of methane captured by the three LRDD boreholes was also high and close to 60% over the longwall mining period, as shown in Fig. 3.4.3.

The methane drainage efficiency of the CM borehole system alone is estimated to be between 25 and 30%. Combined with LRDD boreholes, the results of the DD-MET study suggest that a combined system of CM and LRDD boreholes can capture between 50 to 60% of the total methane liberated from an active longwall panel.

Lessons learned from the analysis of the methane drainage systems at the Staszic-Wujek Coal Mine:

1. Gas at high concentrations of methane can be captured with LRDD boreholes.

2. With the CM and LRDD boreholes, more methane was captured during active longwall mining and lower methane concentrations were measured at the intersection of the longwall face and the return gate road.

3. Combining CM boreholes with LRDD boreholes provides an overall system of draining active longwalls with a capture efficiency of greater than 50%.

4. LRDD boreholes placed between 20 and 35 m above the coal seam in the overlying strata were the most effective

5. Continuous monitoring and adjustment of the methane capture system is necessary to maintain high methane drainage efficiency. This is particularly important when neighbouring longwall panels are mined in succession and their zones of influence above the mining horizon overlap.

6. Because the LRDD boreholes continue to drain gas after completion of mining in a longwall panel, they provide benefits to adjacent longwall panels because of connectivity across their zones of influence.

7. This research clearly demonstrated the effectiveness of LRDD boreholes and their potential to significantly increase the amount of methane captured at mining operations. The application of LRDD boreholes at Polish coal mines will improve mine safety, increase coal production, and reduce methane emissions into the environment.

4. RISK ANALYSIS

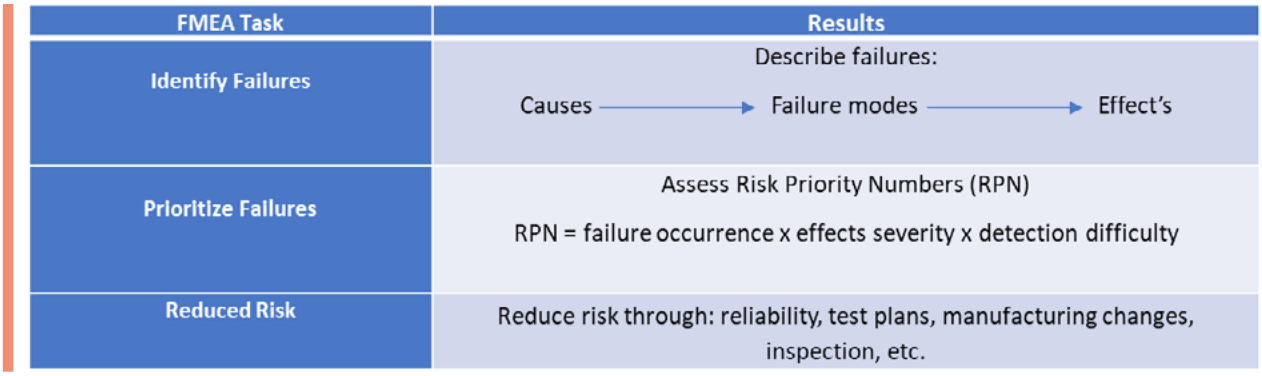
4.1. Potential failure mode analysis

To detect potential failure modes and mechanisms and their effects in the use of this technology, a Failure Mode and Effect Analysis (FMEA) was developed, allowing the identification of how the components, systems, or processes can fail to fulfil their design intent, that is, what is observed to fail or to perform incorrectly:

- To identify the effects that these failures have on the whole process.
- To identify the mechanisms of failures; and finally, what is more important,
- To identify how to avoid the failures and/or mitigate their effects.

Each fault mode identified was ranked according to importance or criticality (Fig. 4.1.1).

Because the identified causes of threats may lead to various effects, the entire analysed technological process was divided into sub-processes: shaft transport, mine transport (underground), drilling rig installation, drilling a borehole for a casing, drilling a borehole up to 100 m, drilling a borehole over 100 m and methane outflow.



FMEA Task	Results
Identify Failures	Describe failures: Causes → Failure modes → Effect's
Prioritize Failures	Assess Risk Priority Numbers (RPN) RPN = failure occurrence x effects severity x detection difficulty
Reduced Risk	Reduce risk through: reliability, test plans, manufacturing changes, inspection, etc.

Fig. 4.1.1. Three significant steps of the FMEA task

A complete FMEA evaluation process was performed for each of them, following the International Standard IEC/ISO 31010, through different experts from Poland and Spain, identifying the failure scenarios that could happen due to hazards occurring during the process.

Each fault mode identified is ranked according to its importance, considering a numeric score that quantifies:

- The likelihood that the failure will occur.
- The likelihood that the failure will not be detected, and
- The amount of harm or damage the failure mode may cause to a person or equipment.

The product of these three scores is the Risk Priority Number (RPN) for that failure mode. The sum of the RPNs for the failure modes is the overall RPN for the process. In the final step of this methodology, the actions and checks are assessed to reduce the hazards' impact on the methane drainage.

As a result, risks were classified into four priorities according to the measures used to assess and compute the risks.

The most critical ones have been assigned FIRST PRIORITY. SECOND PRIORITY was assigned to less critical risks, and the THIRD and FOURTH PRIORITY to the rest of the risks.

The analysis identified the most likely emergency events during drilling for a specific location and work conditions (Table 4.1.1).

Table 4.1.1. List of the most likely emergency events

	Description of the emergency event	The nature of the cause of the event
1.	Difficulties in transporting the drilling rig (too small size of the shaft cage)	Technical, organisational
2.	Difficulties in transporting the drilling rig (too small cross-section of workings)	Technical, organisational
3.	Difficulties in the assembly and installation of the drilling rig (too small dimension of the drilling pocket)	Technical
4.	Insufficient power from the electric power source	Technical, organisational
5.	Insufficient amount of compressed air (low pressure)	Technical, organisational
6.	Not enough water	Technical, organisational
7.	Too much water circulated in the borehole	Technical, organisational
8.	Backfilling the borehole	Natural
9.	Gas blowout into the borehole	Natural
10.	Water outflow from the borehole	Natural
11.	Damage to the drill string	Natural
12.	Disruption of the scrubber circulation	Natural
13.	Fire in the work area	Natural
14.	Power off	Technical
15.	Breakage of the drill string	Technical
16.	Unscrewing the drill string	Technical
17.	Drill bit damage	Technical
18.	Downhole motor failure	Technical
19.	Loss of hole continuity	Geological

Identified emergency events were subjected to further analysis, which enabled assigning them to the occurring sub-processes, such as:

a. Shaft transport.
b. Mine transport (underground).
c. Construction of the drilling rig.
d. Drilling a borehole for the casing.
e. Drilling a borehole up to 100 m long.
f. Drilling a borehole longer than 100 m.
g. Gas blowout.

Risks were summarised in an ordered way, according to their RPN value. The most critical ones have been assigned as FIRST PRIORITY (RPN > 150). They are the following ones:

- In drilling a borehole for a casing pipe, drilling a borehole up to 100 m, drilling a borehole over 100 m, and methane outflow, the critical point is the fire in the work area (RPN 216). The potential cause is the coal self-ignition, and the action must stop the process.
- In drilling over 100 m, the spalling and crumbling of the borehole. The potential cause of this risk is the low compactness of rock mass and the effects of works on the rock mass (RPN 192). The action must be the interruption of the work.
- In the methane outflow, the loss of borehole continuity and the stopping of the flow (RPN 180). The potential cause is the incorrect drilling of a borehole, and the action must improve the supervision of the execution of works.
- In drilling a hole over 100 m with the failure of the drill pipe. The potential cause of this risk is the occurrence of de-stressing (RPN 160). The action must be proper conduct of the work, staff experience, and supervision of the execution of the work.
- In the methane outflow, the loss of borehole continuity and the reduction of methane outflows (RPN 160). The potential cause is the incorrect drilling of a borehole, and the action must improve the supervision of the execution of works.

The SECOND PRIORITY (150 > RPN >100) was assigned to less critical risks, focused mainly on drilling above 100 meters and more related to technical hazards derived from how the technology is implemented. Finally, the THIRD (100 > RPN > 50) and FOURTH PRIORITY (RPN < 50) were assigned to the rest of the risks.

Considering the lessons relevant to DD-MET from the potential failure mode analysis, we should point out the following:

1 The most critical aspects are the fire in the work area, the loss of continuity in the borehole, and pipe failure. Boreholes up to 100 meters pose the most critical risk, even more than for boreholes over 100 meters. This indicates that the proximity to the work face is a critical point the technicians value. These risks are essential because they are linked to natural and geological issues.

2 A second group of less critical risks are focused on drilling above 100 meters. The risk values have a bias or tendency related to the experts to whom the survey was addressed. A technician responsible for installing the pre-drilling system would possibly give more importance to the insufficiency of the energy supply.

3 This analysis shows more of the concern of the technicians in the follow-up of the degassing process and that it may affect the workings of coal exploitation. Less importance is given to the costs and operation of the equipment and machinery used for this work.

4.2. Environmental risk assessment

The DD-MET project focuses on underground LRDD boreholes in overlying coal seams, sandstones or other barren rocks to allow gas draining before, during, and after the mining operations. This applied research has been performed in the facilities of the Staszic-Wujek Coal Mine. Therefore, it is also necessary to carry out a study of the possible effects on the environment.

The Environmental Risk Assessment (ERA) is a systematic approach for assessing and managing risks associated with human health and ecological entities caused by an event occurring in the environment. ERA is the characterisation of adverse health effects that result from human and ecological exposures to environmental hazards.

This study has been carried out by referencing the exploitation of seam 501 and the mine that serves it (Staszic-Wujek Coal Mine), both located south of Katowice. Specifically, it will describe the closest environmental areas where environmental damage could occur, affecting the lives of people and workers and the area's most important natural and landscape resources.

The methodology used to develop this objective is as follows:

1. Description of the geographical setting, topography, hydrographic network, land use, and climate of the study area where the mine is located.
2. Location of the mining facilities, describing their functionality, considering the facilities that manage the mine's ventilation system, and the area where the coal seams 501-510 are extracted and degasified.
3. The most important environmental areas in the south of Katowice that may be affected by mining activity are identified (in total nine areas are identified as Areas of Environmental Interest, ID01 to ID09):
    a. ID 01 - Nature reserve of "Murckowski Forest".
    b. ID 02 - Nature reserve "Ochojec Forest".
    c. ID 03 - The „Sources of Kłodnica River" and other ponds.
    d. ID 04 - Park KWK Staszic with the lake "Barbara".
    e. ID 05 - Katowice Forest Park.
    f. ID 06 - Area of sports airport Muchowiec.
    g. ID 07 - Historical old miner's area "Giszowiec".
    h. ID 08 - Historical old miner's area "Nikiszowiec".
    i. ID 09 - Others: Gardens allotments and cemetery "Murcki".

These areas are described with special mention of their vegetation, water quality, landscape and environmental values.

4. The impact of each of the mine's facilities on areas of environmental interest is assessed. These

impact values are graded into "very high", "high", "medium" and "low", grouping their effect according to four scenarios:

a. Impacts due to the proximity of the urban areas.

b. Impacts due to gas migration and methane degasification.

c. Impacts due to water contamination and groundwater regime.

d. Impacts due to seismicity and ground surface deformation.

5. Finally, remediation measures that can be considered to reduce damage are listed.

The Staszic-Wujek mine is located south of the urban center of Katowice, in the area identified in Fig 4.2.1. It is surrounded by several other mining facilities, such as the Murcki mine, with which it shares mining workings. It is an operating mine, with the coal resources estimated until 2038. The urbanised areas are in red, and the mining and industrial activities are marked in magenta, while green indicates a notable extension of green areas.

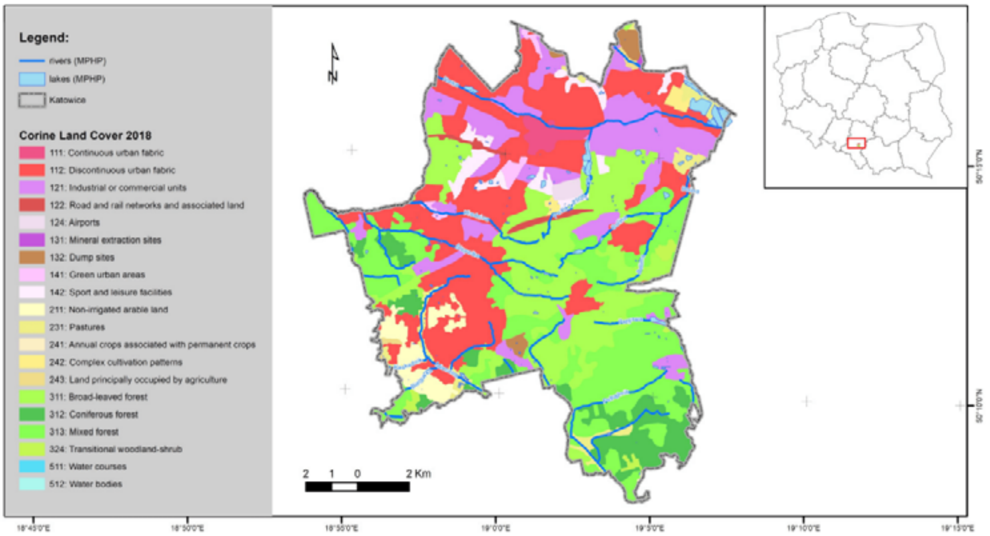


Fig. 4.2.1. Land use and hydrological network around Staszic-Wujek Coal Mine (Corine Land Cover).

Using this methodology, within this mining area of the Murcki - Staszic Coal Mine, we could find the following mining facilities (Fig. 4.2.2):

- Mining Plant. Staszic-Wujek Coal Mine (Shaft I, II).
- Exhaust Shaft IV
- Fan station and the methane drainage injector station near Shaft V.
- Zygmunt Shaft.
- Coal Seam 501-510.

Fig. 4.2.2. Mining facilities and the nearest urban area of the Staszic-Wujek Coal Mine.

Depending on the work related to each of the mining areas and considering different criteria the following tables have been drawn up indicating for each criterion the severity of the level of impact (Low, Medium, High, Very High) using the colour scale of the Table 4.2.1.

Table 4.2.1. Colour scale of each type of impact.

Type of affectation	Colour
Low	🟩
Medium	🟨
High	🟪
Very high	🟥

Several scenarios of affectation have been considered for this purpose:

- Impacts due to the proximity of the mine facilities (Table 4.2.2).
- Impacts due to gas migration and methane degasification (Table 4.2.3).
- Impacts due to water contamination and groundwater regime (Table 4.2.4).
- Impacts due to seismicity and ground surface deformation (Table 4.2.5)

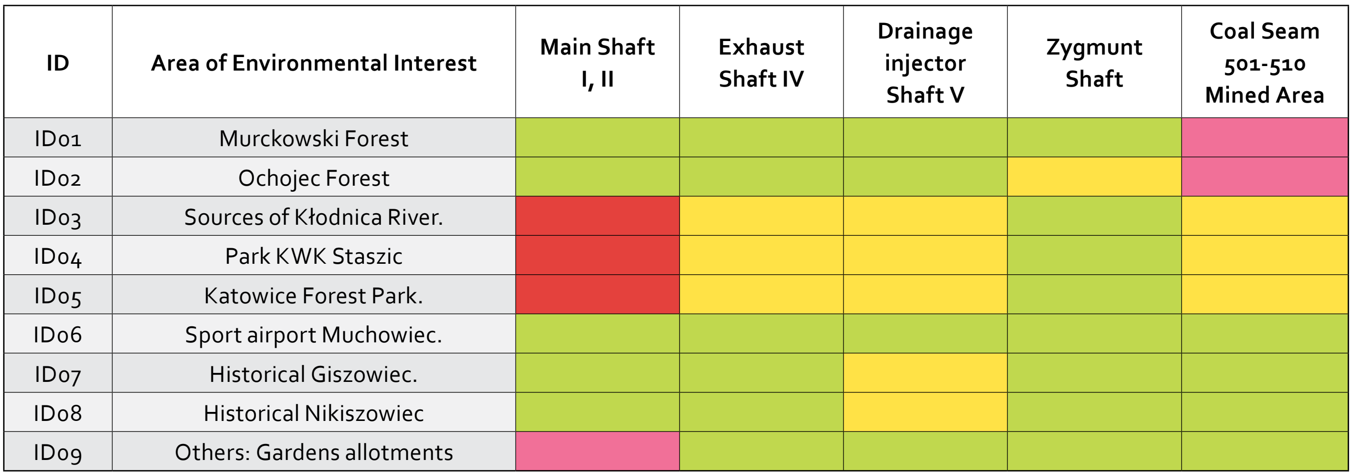
Table 4.2.2. Impacts due to the proximity of the mine facilities.

Area of Environmental Interest ID	Ubication respect the Main Shafts I, II	Distance to Main Shaft I, II	Distance to Exhaust Shaft IV	Distance to drainage injector Shaft V	Distance to Zygmunt Shaft	Distance to 501-510 Mined Area
ID01	South	3.37 Km	4.13 Km	4.88	5.15 Km	0.00 Km
ID02	South-West	4.01 Km	5.38 Km	6.36	1.40 Km	4.20 Km
ID03	South-West	2.81 Km	4.19 Km	5.34	2.78 Km	3.04 Km
ID04	South-West	0.75 Km	2.08 Km	2.05	4.75 Km	2.75 Km
ID05	North	1.98 Km	2.10 Km	0.90	7.00 Km	5.79 Km
ID06	North	1.64 Km	2.55 Km	1.10	5.73 Km	5.33 Km
ID07	East	1.50 Km	0.50 Km	2.18	6.88 Km	3.56 Km
ID08	East	3.73 Km	2.36 Km	2.47	9.20 Km	6.11 Km
ID09	South	2.29 Km	3.15 Km	4.10	4.71 Km	1.37 Km

Table 4.2.3. Impacts due to gas migration and methane degasification.

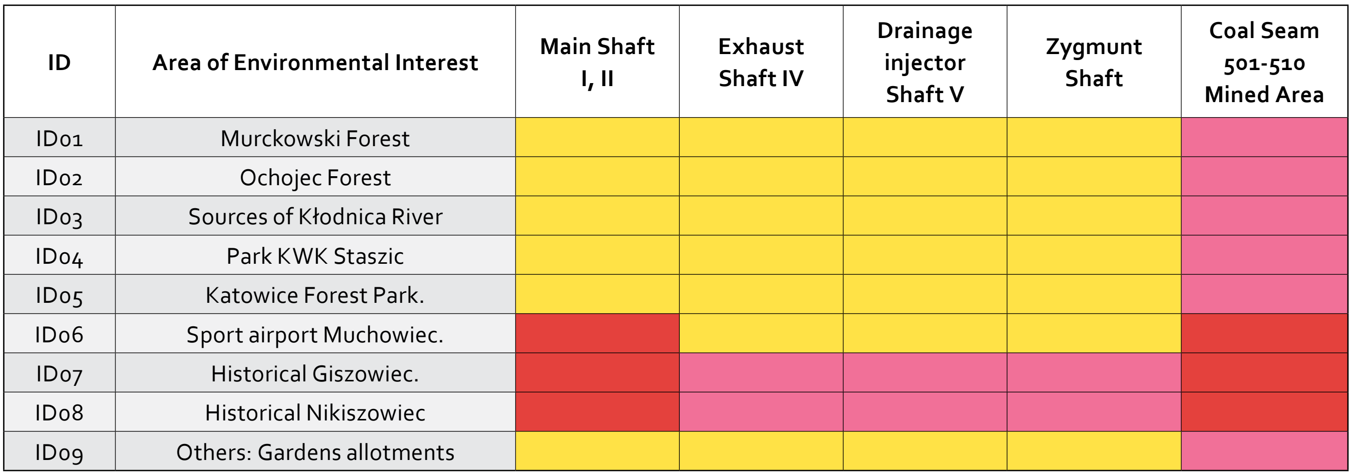
ID	Area of Environmental Interest	Main Shaft I, II	Exhaust Shaft IV	Drainage injector Shaft V	Zygmunt Shaft	Coal Seam 501-510 Mined Area
ID01	Murckowski Forest	🟨	🟩	🟩	🟨	🟥
ID02	Ochojec Forest	🟨	🟩	🟩	🟥	🟨
ID03	Sources of Kłodnica River.	🟨	🟩	🟩	🟪	🟩
ID04	Park KWK Staszic	🟥	🟪	🟪	🟩	🟩
ID05	Katowice Forest Park.	🟪	🟨	🟥	🟩	🟩
ID06	Sport airport Muchowiec.	🟪	🟨	🟥	🟩	🟩
ID07	Historical Giszowiec.	🟪	🟥	🟪	🟩	🟩
ID08	Historical Nikiszowiec	🟨	🟪	🟪	🟩	🟩
ID09	Others: Gardens allotments	🟩	🟩	🟩	🟩	🟨

Table 4.2.4. Impacts due to water contamination and groundwater regime.



ID	Area of Environmental Interest	Main Shaft I, II	Exhaust Shaft IV	Drainage injector Shaft V	Zygmunt Shaft	Coal Seam 501-510 Mined Area
ID01	Murckowski Forest	🟩	🟩	🟩	🟩	🟪
ID02	Ochojec Forest	🟩	🟩	🟩	🟨	🟪
ID03	Sources of Kłodnica River.	🟥	🟨	🟨	🟩	🟨
ID04	Park KWK Staszic	🟥	🟨	🟨	🟩	🟨
ID05	Katowice Forest Park.	🟥	🟨	🟨	🟩	🟨
ID06	Sport airport Muchowiec.	🟩	🟩	🟩	🟩	🟩
ID07	Historical Giszowiec.	🟩	🟩	🟨	🟩	🟩
ID08	Historical Nikiszowiec	🟩	🟩	🟨	🟩	🟩
ID09	Others: Gardens allotments	🟪	🟩	🟩	🟩	🟩

Table 4.2.5. Impacts due to seismicity and ground surface deformation.



ID	Area of Environmental Interest	Main Shaft I, II	Exhaust Shaft IV	Drainage injector Shaft V	Zygmunt Shaft	Coal Seam 501-510 Mined Area
ID01	Murckowski Forest	🟨	🟨	🟨	🟨	🟪
ID02	Ochojec Forest	🟨	🟨	🟨	🟨	🟪
ID03	Sources of Kłodnica River	🟨	🟨	🟨	🟨	🟪
ID04	Park KWK Staszic	🟨	🟨	🟨	🟨	🟪
ID05	Katowice Forest Park.	🟨	🟨	🟨	🟨	🟪
ID06	Sport airport Muchowiec.	🟥	🟨	🟨	🟨	🟥
ID07	Historical Giszowiec.	🟥	🟪	🟪	🟪	🟥
ID08	Historical Nikiszowiec	🟥	🟪	🟪	🟪	🟥
ID09	Others: Gardens allotments	🟨	🟨	🟨	🟨	🟪

Considering the lessons relevant to DD-MET from the environmental impact of mining activity, we should point out the following:

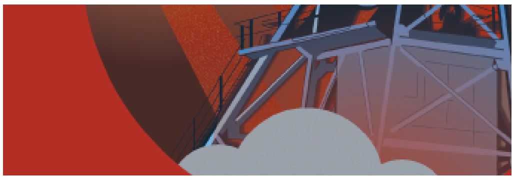
1. Murcki residential district is the most affected by ground settlement and micro-earthquakes. It is located directly above the mined area and is susceptible to atmospheric contamination by residual methane migration through geological fractures. The phenomena of subsidence in this area are essential, and the presence of hospital facilities makes it necessary to take measures to control the deformation of the terrain. Within this district, the most significant environmental risks are in The Murckowski Forest Reserve (ID01). Fortunately, the considerable extension of woodland means these phenomena are less visible than in other built-up areas.

2. Due to its proximity to Shaft V, the two most environmentally sensitive areas may be subject to the adverse effects of air pollution or methane leakage from the degasification network. These areas are located in the district of Giszowiec and the parks in the south-east of Katowice Center. Here, the environmental area of interest that is likely to be most compromised is the Historical old miner's area "Giszowiec" (ID07) and Katowice Forest Park (ID05).

3. Due to its proximity to Shafts I and II, the most environmentally sensitive areas that may be subject to the harmful effects of water contamination are Park KWK Staszic and watercourses in the mining area (ID04).

4. Depending on the prevailing winds in the area where the wind blows from the south-west, the area most prone to atmospheric pollution due to the dispersion of a point source of methane leakage of pollutant fumes will be in the urban area of Giszowiec, Nikiszowiec and north of Myslowice. Here, the environmental areas of interest that are likely to be most compromised are the Historical old miner's area "Giszowiec" (ID07) and the Historical old miner's area "Nikiszowiec" (ID08).

5. LCA AND ECO-EFFICIENCY OF METHANE DRAINAGE TECHNOLOGIES



5.1. Key issues in the life cycle assessment of the LRDD boreholes system

Life cycle assessment is an approach to assess the environmental impact of a product, process, or system from „cradle to grave" from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Such an approach helps to avoid the problem of shifting burdens beyond the gate of a company.

LCA of methane drainage technologies was based on in situ tests performed under the DD-MET project. The LCA was conducted following the International Standards ISO 14040: 2006 and ISO 14044:2006 using SimaPro software and ecoinvent database. The ReCiPe 2016 model (Huijbregts et al. 2017) was applied for impact assessment using both midpoint impact categories and endpoint damage categories. Midpoint indicators (including carbon footprint) focus on single environmental problems, whereas endpoint indicators aggregate impacts into simplified damage categories, enabling application of results in the eco-efficiency analysis and facilitating interpretation. As a result, the values of potential environmental effects and damage to the system in the defined system boundaries in various categories were quantified. The value of damage was used for eco-efficiency calculation.

Regarding methane removal efficiency, the LCA aimed to compare two drainage technologies, CM boreholes and LRDD boreholes. Demonstration field trials have been carried out in the area of longwall in the Murcki-Staszic mine since 2018, in field C at the level of 900 m from two longwalls: Longwall I-C and Longwall II-C, the exploitation of which was carried out until 2022. The drilling of LRDD boreholes was intended to support classic methane drainage. For longwall I-C, five directional wells were made with a total length of 1,706 m and 91 cross-measure boreholes (24 x 4) of a total length 6,489.5 m. For longwall II-C, 4 directional wells were made with a total length of 1,169 m and 80 CM boreholes (20 x 4) with a total length of 5,998.5 m.

There is an important difference between CM and LRDD boreholes, which should be included in the assessment. Namely, directional wells could be retained after cessation of production, and methane continues to be extracted from goafs. As a result, less methane is captured by the ventilation system and emitted into the air. In the case of classic methane drainage, after extraction from the longwall is completed, it is impossible to continue collecting methane using the methane drainage system; thus, the amount of ventilation air methane (VAM) increases. The system boundaries included further methane production from goafs in the case of LRDD boreholes for five years after extraction. Due to a lack of data, increased VAM emission in CM's case was not included.

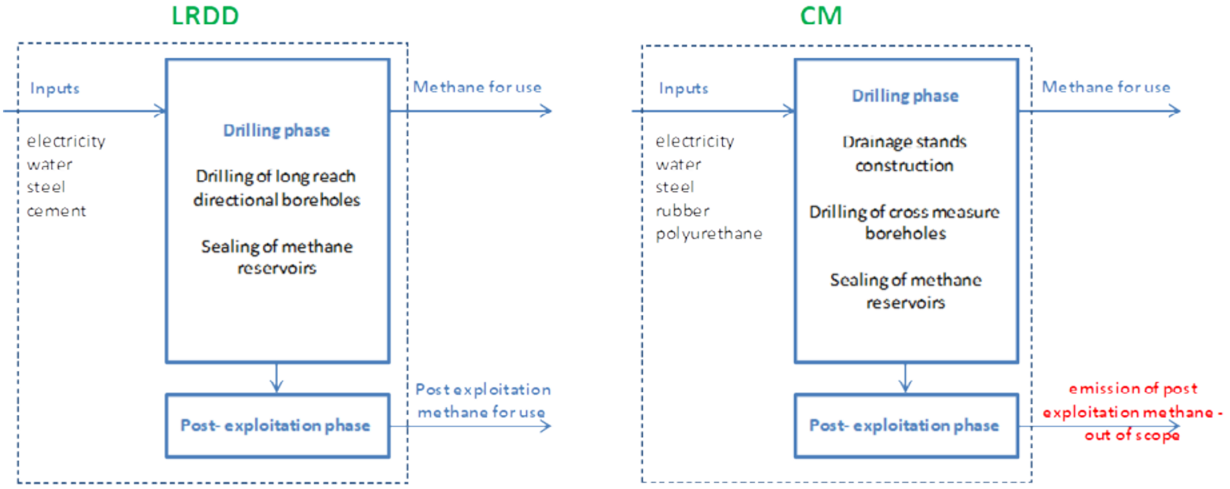


Fig. 5.1.1. System boundaries for LRDD boreholes and CM boreholes.

The function of the system is the production of methane. The functional unit is the volume of pure methane: 1 m^3 CH_4 (100%). System boundaries are presented in Fig. 5.1.1.

Methane drainage requires the installation of pipes, sealing, compressor operation, and drilling activities. Electricity is necessary to power the pump, which creates negative pressure in the methane drainage wells – Polish energy mix was assumed. During the test technology, water was used from the mine fire protection system, and used water was processed by the mine drainage system. No additives were used for drilling operations. As an output, a stream of methane is produced. Data from literature and the market were used to convert the amount of materials to units adjusted to the database. Background processes were modeled using the ecoinvent database. Table 5.1.1 presents primary data applied to calculations.

Environmental impact was calculated using the ReCiPe 2016 model. Midpoint impact values are presented in Table 5.1.2 and in Fig. 5.1.2. Endpoint damage values are presented in Table 5.1.3.

Tab. 5.1.1. Inputs and outputs for Wall I-C and II-C.

	CM IC	LRDD IC	CM IIC	LRDD IIC	unit
OUTPUT					
Methane (100%)	912 916,8	7 350 000	1 397 621	6 380 000	m^3
INPUTS					
Steel	2 230	690	1 860	276	kg
Rubber	30		25		kg
Polyurethane	229		192		kg
Cement		3 000		1 200	kg
Water		10 500 000		10 500 000	m^3
Electricity	33 100	116 000	30 600	46 500	kWh

Tab. 5.1.2 Characterization results per 1 m3 CH4 (100%); ReCiPe 2016 Midpoint (H)

Impact category	Unit	I-C CM	I-C LRDD	II-C CM	II-C LRDD
Global warming	kg CO2 eq	0,041618	0,015951	0,024778	0,007402
Stratospheric ozone depletion	kg CFC11 eq	8,37E-09	3,22E-09	4,99E-09	1,50E-09
Ionizing radiation	kBq Co-60 eq	0,000971	0,000388	0,00058	0,00018
Ozone formation, Human health	kg NOx eq	8,60E-05	3,23E-05	5,11E-05	1,50E-05
Fine particulate matter formation	kg PM2.5 eq	7,29E-05	2,80E-05	4,35E-05	1,30E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	8,72E-05	3,25E-05	5,18E-05	1,51E-05
Terrestrial acidification	kg SO2 eq	0,000202	8,14E-05	0,000121	3,78E-05
Freshwater eutrophication	kg P eq	4,80E-05	1,99E-05	2,88E-05	9,21E-06
Marine eutrophication	kg N eq	3,14E-06	1,24E-06	1,88E-06	5,74E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0,041262	0,014308	0,024334	0,006639
Freshwater ecotoxicity	kg 1,4-DCB	0,00176	0,000639	0,001044	0,000296
Marine ecotoxicity	kg 1,4-DCB	0,002406	0,00087	0,001426	0,000404
Human carcinogenic toxicity	kg 1,4-DCB	0,005199	0,001327	0,003	0,000616
Human non-carcinogenic toxicity	kg 1,4-DCB	0,060406	0,024668	0,036239	0,011449
Land use	m2a crop eq	0,000702	0,000272	0,000419	0,000126
Mineral resource scarcity	kg Cu eq	0,000173	1,59E-05	9,51E-05	7,36E-06
Fossil resource scarcity	kg oil eq	0,010416	0,003968	0,006207	0,001841
Water consumption	m3	0,001169	0,000483	0,000702	0,000224

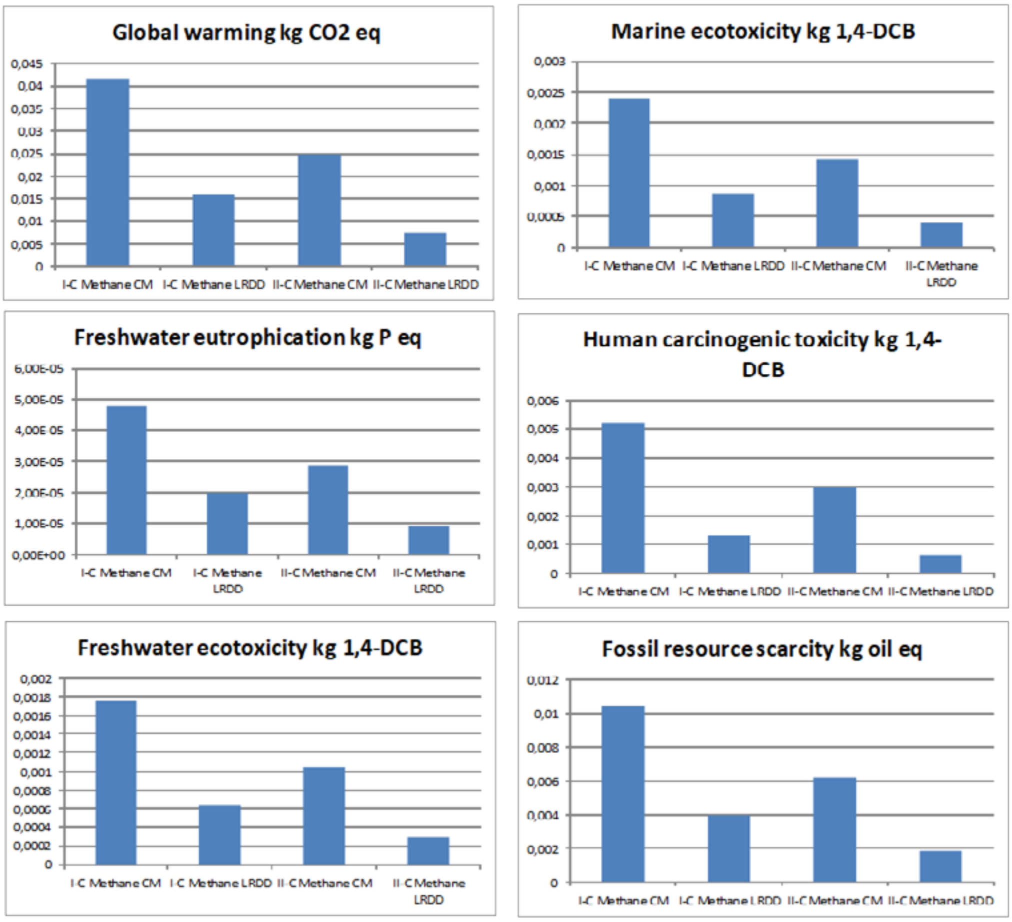


Fig. 5.1.3. Characterisation results per 1 m³ CH_4 (100%)

Table 5.1.3. Single score results per 1 m³ CH_4 (100%); ReCiPe 2016 Endpoint (H/A)

Damage category	Unit	I-C CM	I-C LRDD	II-C CM	II-C LRDD
Total	mPt/m3	1,998	0,735	1,186	0,341
Human health	mPt/m3	1,932	0,709	1,146	0,329
Ecosystems	mPt/m3	0,058	0,023	0,035	0,011
Resources	mPt/m3	0,008	0,002	0,005	0,001

The lessons relevant to DD-MET from the life cycle assessment of LRDD boreholes

1 LRDD technology was assessed in comparison to CM boreholes based on a demonstration performed in the Murcki-Staszic Coal Mine. The tested technology of LRDD boreholes lead to lower environmental impact in each impact category, considering overall damage expressed as a single score.

2 The results obtained were sensitive to electricity consumption and methane production. Post-exploitation methane production in the case of LRDD strongly impacts the environmental assessment of the technology.

3 Further potential reduction of the environmental footprint of methane drainage technologies can be achieved by increasing the energy efficiency of drilling and pumping and using renewable energy sources.

5.2. Selection of methane drainage technology based on the results of the eco-efficiency assessment

Eco-efficiency assessment is a new method of evaluating the effectiveness of technologies, products, and processes, which allows for an integrated economic and environmental assessment taking into account the life cycle of the technology or product. The World Business Council for Sustainable Development (WBCSD) defined eco-efficiency in 1991 as providing products and services competitively that meet human needs and enhance quality of life, reducing environmental impact and resource consumption throughout the life cycle.

Eco-efficiency analysis integrates two of the three elements of sustainability: economic and environmental (Fig. 5.2.1).

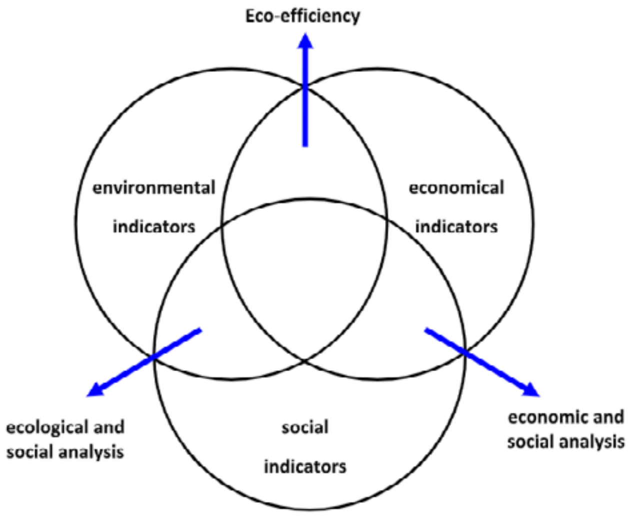


Fig. 5.2.1. Elements of sustainable development

Eco-efficiency links the primary goal of enterprises, which is profit and production profitability, with an environmental approach so that the enterprise's decision-makers can create innovative products or technologies that also meet environmental criteria. Development- and innovation-oriented companies strive to make the eco-efficiency of their technologies or products higher and higher, which means that the profits of their operations will increase and the environmental impact will be less and less.

The applicable terminology and methodological framework for eco-efficiency assessment are presented in PN-EN ISO 14045:2012 „ Environmental management - Eco-efficiency assessment of product systems - Principles, requirements and guidelines." This European Standard defines an eco-efficiency index as a measure that relates the result of an environmental assessment of a product or technology to the value of the product or technology being analysed.

A proprietary methodology developed at Central Mining Institute in Katowice was used to assess the eco-efficiency of methane drainage technologies. The process is in accordance with PN-EN ISO 14045:2012 and combines the results of two analyses:

- Life cycle assessment (LCA), which was discussed in the previous section 5.1,
- Life cycle costing (LCC).

The life-cycle costs of the methane drainage technologies analysed were estimated using the Dynamic Generation Cost (DGC). DGC is equal to the price to generate discounted revenues similar to discounted costs. DGC shows the technical cost of obtaining a unit of product, in this case, 1 m3 of methane captured by the methane drainage system.

From the adopted methodology for assessing eco--efficiency, the following relationship emerges: the lower the value of the eco-efficiency index, the less eco-efficient the methane drainage technology is.

For the purpose of eco-efficiency analyses, data were obtained from the methane drainage of the I-C and II-C longwall panels in coal seam 501 at 900 m depth in the Staszic-Wujek Coal Mine, which was carried out using two methods:

- methane drainage using Cross-Measure (CM) boreholes,
- methane drainage using Long Reach Directionally Drilled (LRDD) boreholes

The following data were used to calculate the eco-efficiency of the two methane drainage technologies:

- Results of the life cycle assessment (LCA),
- Capital expenditures (CAPEX) and operating costs (OPEX) associated with the construction and operation of the two methane drainage systems,
- Quantities of methane captured during the extraction from the I-C and II-C longwall panels and projected for the following years after extraction.

Table 5.2.1 presents the results of the eco-efficiency analysis along with the results of the LCA and LCC analyses that were used to calculate the eco-efficiency indicators.

Tab. 5.2 1. The results of eco-efficiency analysis of methane drainage methods

Scenario		DGC EUR/m³ CH_4	LCA mPt/m³ CH_4	Eco-efficiency m⁶/EUR*mPt
Longwall panel I-C	CM boreholes	0.62	1.998	0.80
	LRDD boreholes	0.10	0.735	14.28
Longwall panel II-C	CM boreholes	0.35	1.186	2.38
	LRDD boreholes	0.07	0.341	43.43

The calculation results indicate that the methane drainage using LRDD boreholes is more eco-efficient than the methane drainage using CM boreholes. And the difference is significant. This is illustrated by the graphical interpretation of the results presented in Fig. 5.2.2.

The higher eco-efficiency of methane drainage using LRDD boreholes is made up of better results of the LCA and LCC analyses, expressed as the DGC indicator. This is influenced by higher methane production (positive impact on the results of LCA and LCC analyses) and lower costs of performing de-methanation using LRDD boreholes (positive impact on the development of LCC analyses).

The obtained results of the eco-efficiency analyses were subjected to sensitivity analyses.

It was found that the largest impact on eco-efficiency is the volume of methane production. The greater the amount of methane extracted, the lower the unit cost of methane expressed by the DGC index and the environmental impact determined by the LCA analysis.

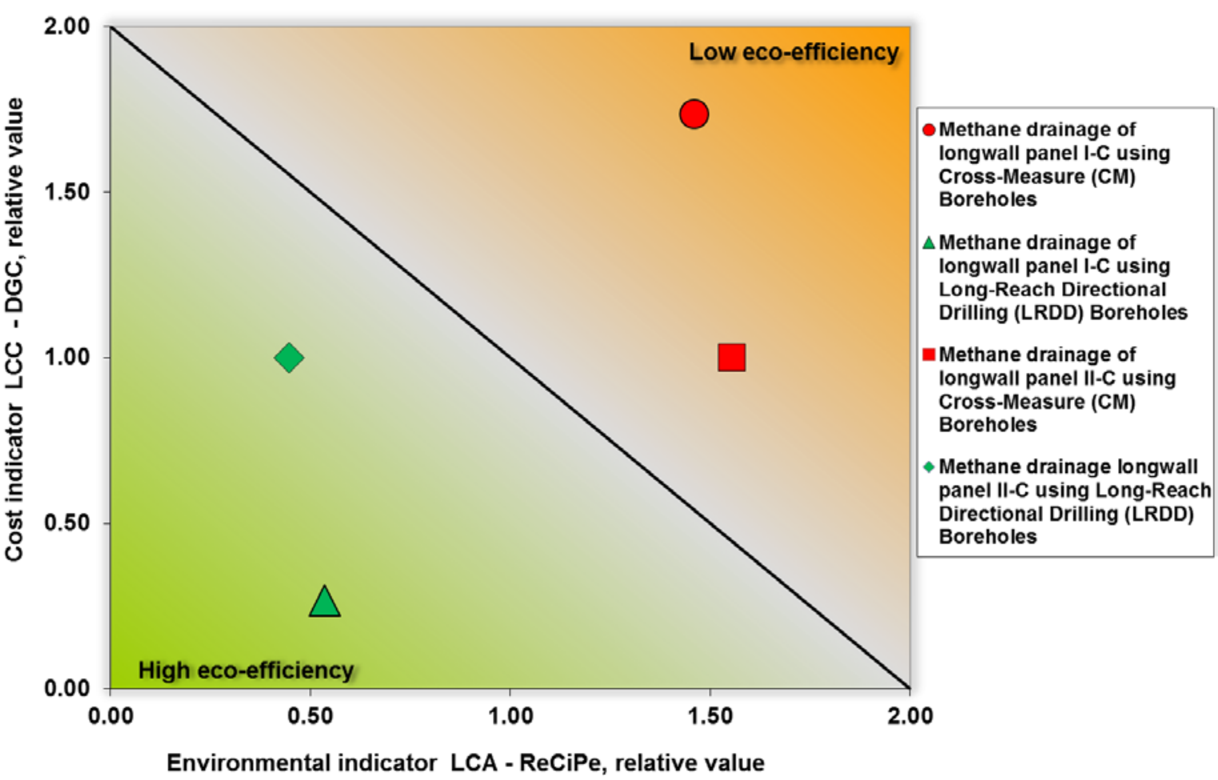


Fig. 5.2.2. Graphic interpretation of the eco-efficiency results of the methane drainage of longwall panels I-C and II-C in Staszic-Wujek Coal Mine

The lessons relevant to DD-MET from the eco-efficiency assessment of LRDD boreholes

1 LRDD technology was assessed in comparison to CM boreholes, based on demonstration performed in the Staszic-WujekCoal Mine. The tested technology LRDD boreholes proved more eco-efficient than conventional CM technology.

2 The advantage of the technology using LRDD boreholes is mainly due to the possibility of extracting methane after coal extraction from the exploited longwall. This is impossible with technology using CM boreholes because the boreholes used for methane drainage are destroyed during coal extraction. In addition, technology using CM boreholes requires drilling a much larger number of boreholes, the total length of which is much greater than with technology using LRDD boreholes.

3 In the case of methane drainage technologies, preference should be given to technologies that enable methane capture even after coal extraction from the target longwalls is completed. The captured methane can be used economically and generate financial benefits (production of heat and electricity). The captured methane does not go into the mine's ventilation system and then into the atmosphere. This reduces the negative impact of the mine on the environment.

6. ECONOMIC ANALYSIS

6.1. Cost and efficiency of methane drainage

This section summarises the feasibility study of the advanced methane drainage strategy employing underground LRDD boreholes technology compared to traditional technologies such as CM boreholes and Drainage Galleries.

The three methodologies' drainage efficiency and economic costs were first modelled using data from different exploitations to achieve this goal. It has to be remarked that although LRDD boreholes is always used in combination with CM boreholes, an ex-post analysis was also developed for this technology considering its results independent from CM boreholes, something that does not happen in actual mining operations.

To establish a comparison of the cost and efficiency of methane drainage using a generic case of a coal seam designed with several consecutive coal panels, excavated with a crosswise system, with a collapsed roof and with the following parameters: Coal panel height between 3 and 4 m; Coal panel length of around 160 m; Longwall run of 400 m, was used. The comparison is presented in Table 6.1.5.

Tab. 6.1.5. Comparing the different alternatives.

Parameter	CM boreholes	Drainage gallery	LRDD boreholes	LRDD + CM boreholes
Number of boreholes	Five every 20 m	1	2 LRDD	2 + 5 every 20 m
Length of each borehole	80 m	-	380 m	380 m + 80 m
Total length of boreholes	16,000 m	450 m	760 m	760 m + 16,000 m
Duration	2.6 months	2.2 months	2.5 months	2.5 + 2.6 months
Cost of drilling	49 €/m	2,283 €/m	544 €/m	544 + 49 €/m
Total cost	782,660 €	1,027,241 €	413,070 €	1,195,730 €
Drainage efficiency	32.87%	62.97%	22.86%	46.81%

Fig. 6.1.1 presents the Cost-efficient distribution function of LRDD boreholes.

On the other hand, Fig. 6.1.2 presents the inputs ranked by the effect on output mean for the Cost-efficient relation of the different alternatives analysed.

Based on these results, it can be observed that the highest Cost-efficient relation is obtained by the Drainage Galleries with a baseline of 0.061 and a standard deviation of 0.003; it is followed by the LRDD boreholes with almost the same baseline of 0.060, although with a much higher standard deviation of 0.053; then, CM boreholes presents a baseline of 0.042 with a standard deviation of 0.004; finally, LRDD + CM boreholes present a baseline of 0.039 and a standard deviation of 0.015.

These figures should be taken into account altogether with the drainage efficiency. The highest one corresponds to Drainage Galleries with a mean of 62.97% and a standard deviation of 0.57%, as presented in Fig. 6.1.3; LRDD + CM boreholes follow it with a mean of 46,81% and a standard deviation of 16.71%; then, CM boreholes with a mean of 32.87% and a standard deviation of 3.27%; finally, LRDD boreholes with a mean of 22.86%, and a standard deviation of 19.06%.

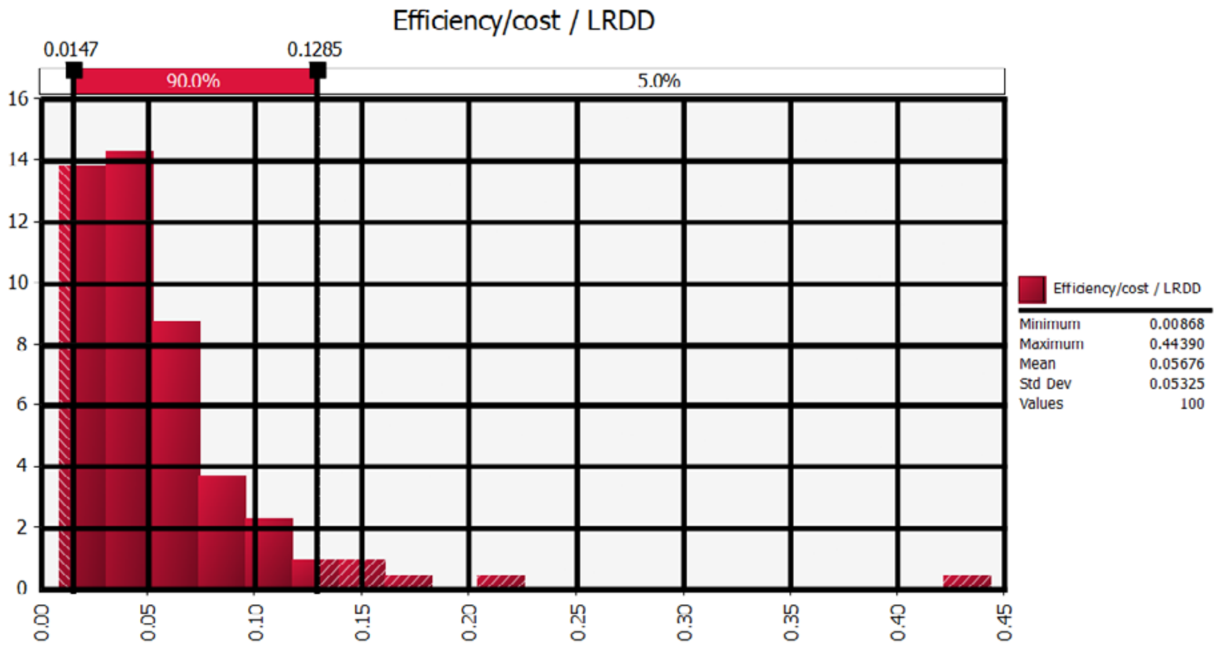


Fig. 6.1.1. Cost-efficient relation of LRDD boreholes.

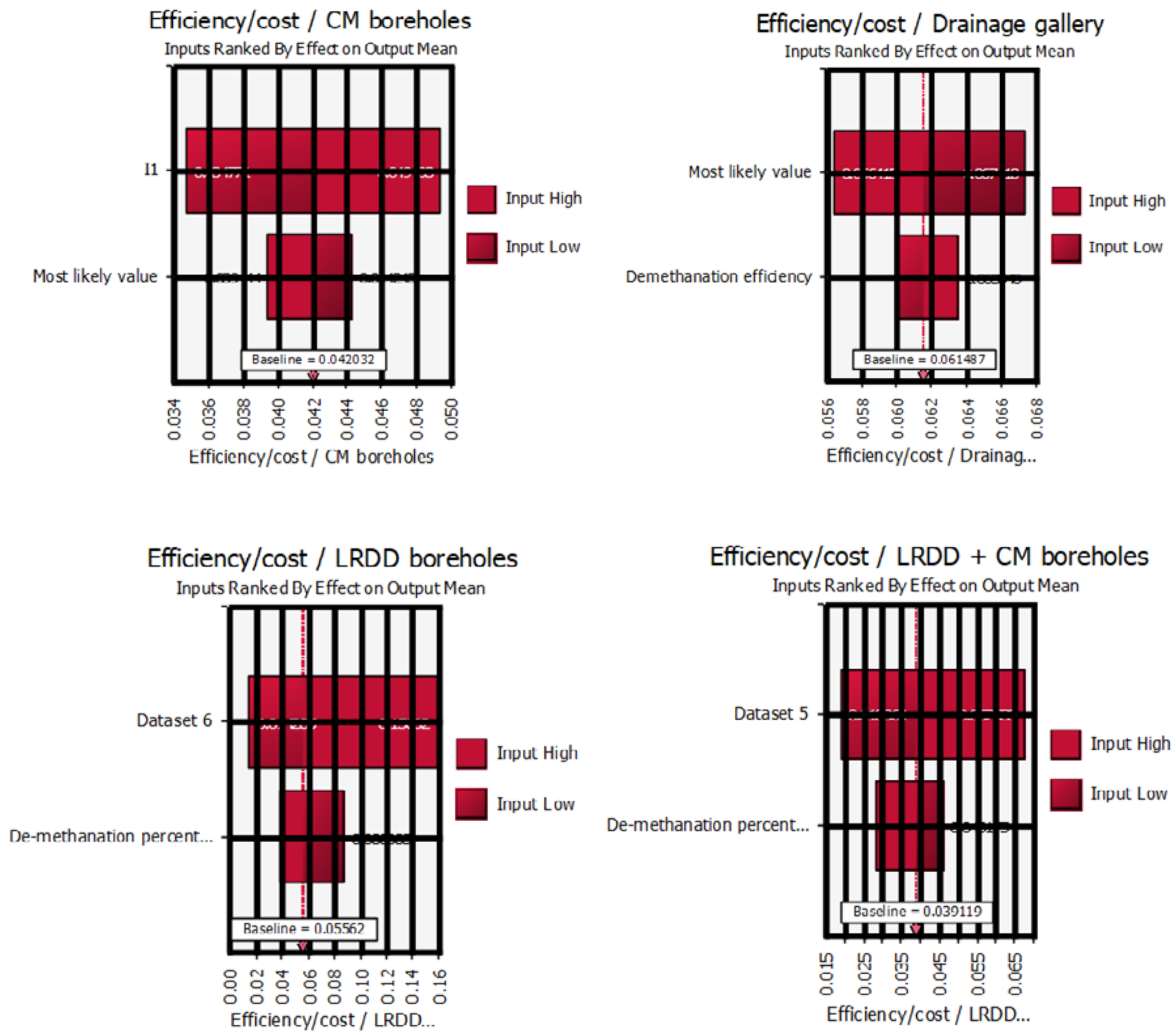


Fig. 6.1.2. Effect on output mean for the Cost-efficient relation of the four alternatives analysed.

However, to evaluate which technology will be more attractive for a specific longwall, the level of in situ methane content should be previously considered to estimate the permissible methane emission and the amount of methane the methane drainage system should drain.

Simultaneously, the cost of emitting the non-drainage methane, increasing the amount of VAM, should also be considered.

Concluding, the three methodologies' de-methanation efficiency and economic costs were modelled using data from different exploitations. Thus, it was possible to undergo a cost-efficiency analysis of the different alternatives to classify them. It has to be remarked that although LRDD boreholes are always used in combination with CM boreholes, it was also analysed alone, which does not happen in actual mining operations.

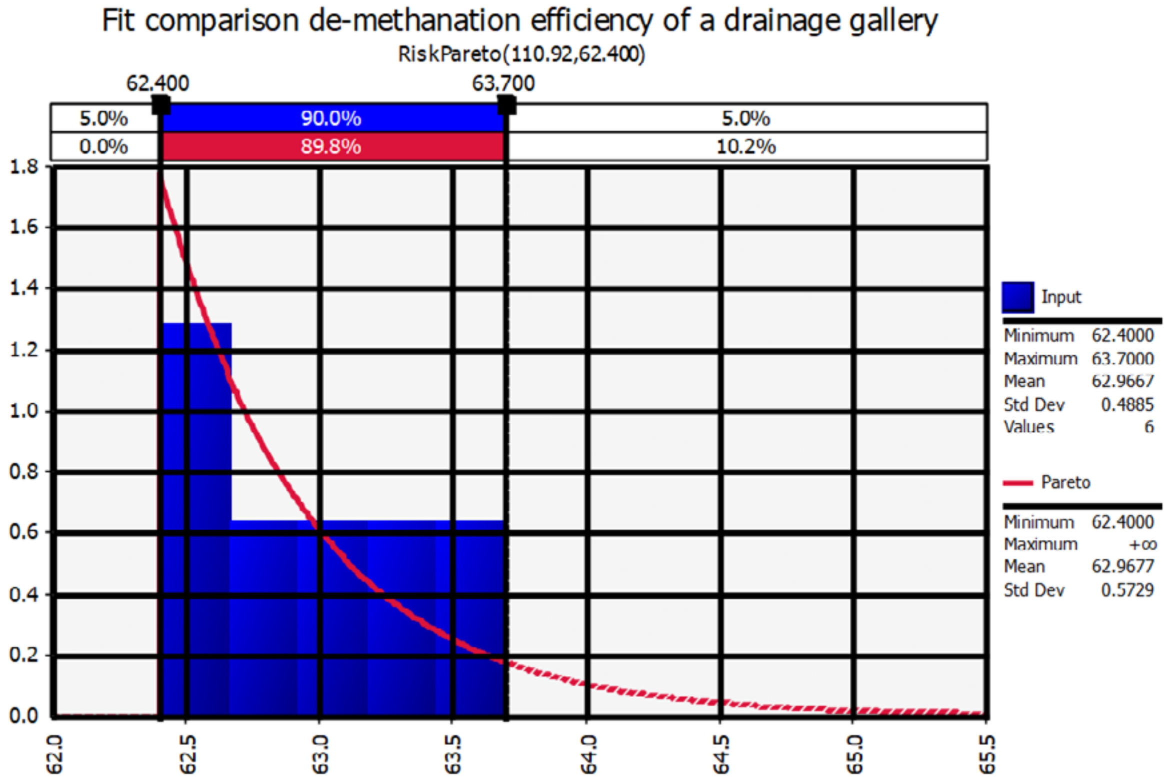


Fig. 6.1.3. Fit comparison de-methanation efficiency of a drainage gallery.

The lessons relevant to DD-MET from the cost and efficiency analysis of methane drainage are:

1 The highest Cost-efficient relation is obtained by the Drainage Galleries with a baseline of 0.061 and a standard deviation of 0.003; it is followed by the LRDD boreholes with almost the same Baseline of 0.060, although with a much higher standard deviation of 0.053; then, CM boreholes presents a baseline of 0.042 with a standard deviation of 0.004; finally, LRDD + CM boreholes present a baseline of 0.039 and a standard deviation of 0.015.

2 LRDD boreholes have a high standard deviation, which, although high, does not happen simultaneously at the same level as the CM boreholes made; thus, further studies are needed to reduce the variability of LRDD borehole results.

3 Considering the drainage efficiency, the highest one corresponds to Drainage Galleries with a mean of 62.97% and a standard deviation of 0.57%; LRDD + CM boreholes follow it with a mean of 46,81% and a standard deviation of 16.71%; then, CM boreholes with a mean of 32.87% and a standard deviation of 3.27%; finally, LRDD boreholes with a mean of 22.86%, and a standard deviation of 19.06%.

4 However, to evaluate which technology will be more attractive for a specific longwall, the level of methane-bearing capacity should be previously considered to estimate the permissible methane emission and the amount of methane the methane drainage system should drain. Simultaneously, the cost of emitting the non-drainage methane, increasing the amount of VAM, should also be considered.

5 A Drainage Gallery is the most efficient, cost-efficient, and reliable technology for highly methane-rich longwalls with high extraction rates when at least 60% of the methane must be drained. However, the galleries should be excavated above the exploited seam in an accompanying non-industrial seam (not intended for exploitation), as if the excavation is done entirely in rock, the excavation cost will rocketeer. CM boreholes are the second most reliable technology to achieve drainage efficiencies of around 35%.

6 When drainage efficiencies around 40% or higher are needed, combining LRDD and CM boreholes could be considered an alternative, although unreliable. Further research and experiments should be developed on LRDD boreholes to achieve more reliable results and increase drainage efficiency.

7 The costs will be reduced when mining companies start developing by their means LRDD boreholes. Thus, if a reliable increase in drainage efficiency is also achieved, they could soon be considered a more exciting technology than CM boreholes and, combined with CM boreholes, a more attractive technology than Drainage Galleries.

6.2. Cost/benefit analysis regarding GHG emissions

A cost/benefit analysis regarding GHG emissions was developed using a three-step calculation:

1. Addressing the cost of draining the methane that will not be emitted into the atmosphere.

2. Considering the Global warming potential (GWP) of methane (100-year time horizon), meaning that the emission of 1 metric ton of methane to the atmosphere equals the impact of 28 metric tons of CO2, according to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, 2014.

3. Monetizing the non-emitted CO2 to the atmosphere using the price of carbon offsets given by the EU emissions trading system, which is the world's first primary carbon market and remains the biggest one, considering the avoided cost of the energy self-production effect which could be estimated in approximately the 90% of the cost of energy purchase.

After analysing the costs of methane drainage by external companies, obtaining the distribution function for the cost of drainage of 1 t of CH4 was possible. Using the Akaike information criterion (AIC), the distribution that best fits the data, which has a mean of 368.39 €/t, is an exponential distribution with a beta value of 250.15 and a domain shift of 93.239, as shown in Fig. 6.2.1, that presents a mean of 343.39 €/t.

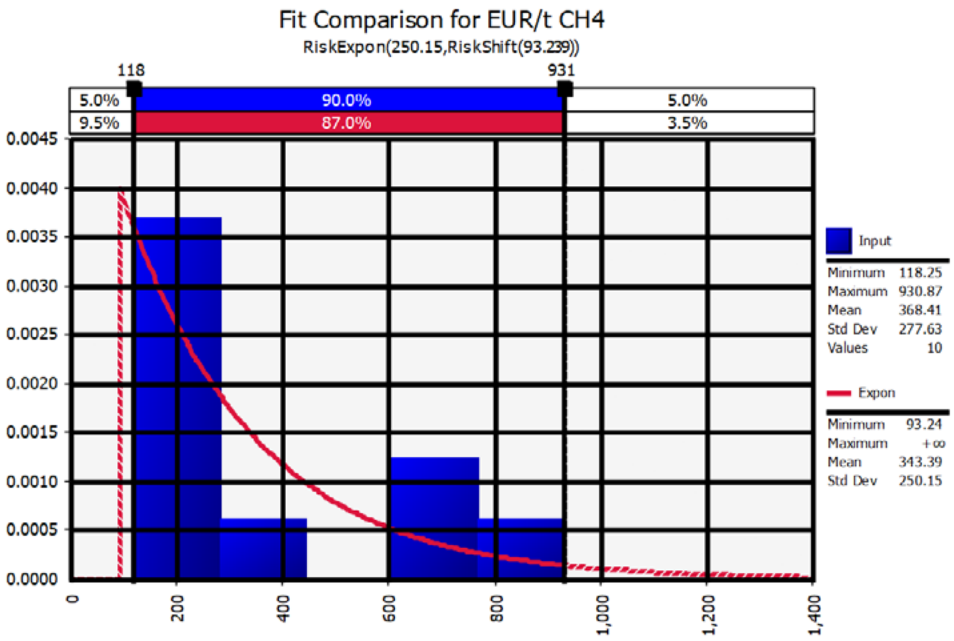


Fig. 6.2.1. The distribution function for the cost of draining 1 t of methane.

In multi-gas studies, a method is needed to compare greenhouse gases with different atmospheric lifetimes and radiative properties. Ideally, the method would allow for substitution between gases to achieve mitigation cost reductions, although more is needed to ensure equivalence in measuring climate impact. Different methods have been proposed, along with their advantages and disadvantages.

Using the Akaike information criterion (AIC), the distribution that best fits the prices of EU Emissions Trading System (ETS) Phase 4, which has a Mean of 84.135, is an Extrem value min distribution with location parameter alpha of 86.9341 and shape parameter beta of 5.0294, as shown in Fig 6.2.2, with a mean of 84.031 €/t CO2.

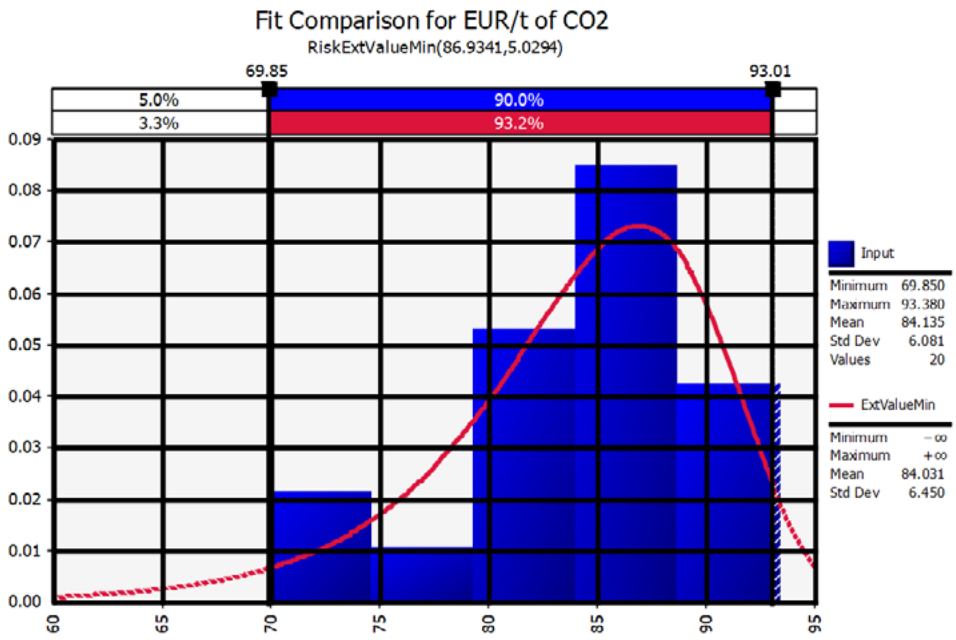


Fig. 6.2.2. Fit comparison for the price of EU emission allowances from January 2022 till August 2023.

The value of 1t of non-emitted methane, according to the EU Emissions trading system, will be:

27.25 t CO2-eq x 84.031 EUR/t CO2-eq = 2,290 EUR/t CH4

The energy savings via the combustion of 1t CH4, with a 75% efficiency using CHP systems and 90% savings related to the cost of electricity (according to Eurostat, electricity prices in Poland for non-household consumers during the second semester of 2022 were 0.1122 €/kWh or 112.2 €/MWh), will be:

15.42 MWh x 0.75 x 112.2 €/MWh x 0.9 = 1,168 €/t CH4

Thus making a total economic value of non-emitted methane of:

2,290 €/t CH4 + 1,168 €/t CH4 = 3,458 €/t CH4

As the average cost of drainage of 1t of CH4 reported for external companies was 343.39 €/t, it only represents 10% of the economic value of non-emitted methane. Thus, with current EU allowances and electricity prices, there is no doubt that any effort addressing the capture and combustion of CH4 is completely worth it.

The lessons relevant to DD-MET from the cost-benefit analysis regarding GHG emissions of methane drainage are:

1. The average cost of drainage of 1t of CH4 reported for external companies was 343.39 €/t, representing only 10% of the economic value of non-emitted methane. Thus, with current EU allowances and electricity prices, there is no doubt that any effort addressing the capture and combustion of CH4 is entirely worth it.

2. However, with the current energy prices, only the energy savings via the combustion of methane justify any effort to address methane capture.

7. CONCLUSIONS/OUTLOOK

Although the coal mining sector in Poland has been gradually shrinking for the past three decades, the share of coal in the Polish energy mix is still significant, and coal itself is a key raw material in ensuring Poland's energy security. The extraction of the coal, however, is becoming increasingly challenging as mining deep gassy coal seams requires a proper methane control strategy to ensure safe working conditions. Modern coal mining companies also recognise the challenges they are facing regarding the decarbonisation of the energy sector in the coming years toward European environmental objectives and global efforts addressing climate change.

Coal mining companies are now adopting holistic gas control strategies to meet these challenges and ensure a smooth coal phaseout transition implementation. These strategies integrate underground gas control, methane utilisation, and reductions of harmful GHG emissions.

The results of the DD-MET project show a successful case study from Staszic-Wujek Coal Mine, where new technology of LRDD boreholes was implemented to benefit three areas: safety, economics, and the environment.

The key findings of the project are as follows:

- Geological modellng and simulations provide an effective tool for optimising LRDD technology regarding methane drainage efficiency, trajectories of the LRDD boreholes, and their stability.
- In the studied longwalls, the LRDD boreholes outperformed the CM boreholes in two key ways:

Higher Methane Production: The LRDD boreholes generated over twice the volume of methane compared to the CM boreholes.

Better Methane Quality: The methane produced by the LRDD boreholes had a higher quality, with an average of 82 % methane in the drained gas, as opposed to the CM boreholes, which had an average of only 30% methane in the drained gas.

- LRDD boreholes placed between 20 and 35 m above the coal seam in the overlying strata were the most effective in methane drainage.
- Combining CM boreholes with LRDD boreholes provides an overall system of draining active longwalls with a capture efficiency of greater than 50%. It also lowers methane concentrations measured at the intersection of the longwall face and the return gate road.
- Because the LRDD boreholes continue to drain gas after completion of mining in a longwall panel, they provide benefits to adjacent longwall panels because of connectivity across their zones of influence.
- This research clearly demonstrated the effectiveness of LRDD boreholes and their potential to significantly increase the amount of methane captured at mining operations. The application of LRDD boreholes at Polish coal mines will improve mine safety, increase coal production, and reduce methane emissions into the environment.
- The potential failure mode analysis identified the most critical aspects that can negatively affect the LRDD technology such as fire in the work area, the loss of continuity in the borehole, and pipe failure linked to natural and geological conditions.
- The environmental risk assessment identified the key areas that can be mining activities including ground settlement and micro-earthquakes, atmospheric pollution by CMM, and water contamination.
- LCA and Eco-efficiency of methane drainage technologies pointed out that tested LRDD technology, compared to CM boreholes, led to lower environmental impact in each of the studied impact categories. The post-exploitation methane production of LRDD boreholes strongly impacts the environmental assessment, and thus, preference should be given to technologies that enable methane capture even after coal extraction from the longwalls is completed. The captured methane can be used economically and generate financial benefits (production of heat and electricity). The captured methane does not go into the mine's ventilation system and then into the atmosphere. This reduces the negative impact of the mine on the environment.
- The highest Cost-efficient relation was obtained by the Drainage Galleries followed by the LRDD boreholes, CM boreholes, and finally, LRDD + CM boreholes. The costs will be reduced when mining companies start developing by their means LRDD boreholes. Thus, if a reliable increase in drainage efficiency is also achieved, they could soon be considered a more exciting technology than CM boreholes

and, combined with CM boreholes, a more attractive technology than Drainage Galleries.

- The cost-benefit analysis regarding GHG emissions of methane drainage shows that the average cost of drainage of 1t of CH_4 reported for external companies was 343.39 €/t, representing only 10% of the economic value of non-emitted methane. Thus, with current EU allowances and electricity prices, there is no doubt that any effort addressing the capture and combustion of CH_4 is entirely worth it.

The main advantages of applying such LRDD technology are:

1. Cost Reduction:
Substitutes the time-consuming and expensive standard ventilation system preparations, eliminating the need for different drainage technologies before, during, and after mining.

2. Greenhouse Gas Emission Reduction:
Achieves more efficient gas drainage from coal seams and surrounding gas-bearing strata, reducing GHG emissions compared to conventional methods.

3. Efficient Gas Utilisation:
Enables the effective use of coal mine methane-collected gas for electricity, heat, or cooling production. Borehole drilling streamlines gas intake and distribution through pipelines.

4. Operational Continuity:
Minimises the need for downtime during mining operations.

5. Cost Savings:
Reduces drilling costs by avoiding the expense of drilling deep directional boreholes from the surface.

6. Enhanced Safety:
Mitigates methane hazards, enhancing workplace safety.

7. Extended Gas Drainage Range:
Allows for methane drainage near the working longwall and surrounding regions after coal exploitation.

REFERENCES

Burchart-Korol D. 2011. Application of Life Cycle Sustainability Assessment and Socio- Eco-Efficiency Analysis in Comprehensive Evaluation of Sustainable Development, Journal of Ecology and Health, 3, 107-110.

Czaplicka-Kolarz K., Burchart-Korol D., Krawczyk P. 2010. Metodyka analizy ekoefektywności. Journal of Ecology and Health, 6, 267–272.

European Commission – Joint Research Centre – Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment – Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union, 2010

Huijbregts M.A.J., Steinmann Z.J.N., Elshout P.M.F. et al. 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y

ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework; International Standard Organization, Geneve, 2006.

ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines, International Organisation for Standardisation (ISO), Geneve, 2006.

Iyyanki V. Krishna K., Manickam V. 2017. Chapter Five – Life Cycle Assessment, Editor(s): Iyyanki V. Krishna K., Manickam V., Environmental Management, Butterworth-Heinemann, 2017, Pages 57-75, ISBN 9780128119891, https://doi.org/10.1016/B978-0-12-811989-1.00005-1.

Leśniak G., Brunner D. J., Topór T., Słota-Valim M., Cicha--Szot R., Jura B., Skiba J., Przystolik A., Lyddall B., Plonka G. 2022. Application of long-reach directional drilling boreholes for gas drainage of adjacent seams in coal mines with severe geological conditions. International Journal of Coal Science & Technology, 9 (1), 1-14.

Makówka J., Bukowska M. 2022. DD-MET Deliverable D.6 Task 2.4 Measurement of prevailing stress and geomechanical parameters.

Nawrat S. Kuczera Z. Łuczak R., Życzkowski P., Napiera S., Gatnar K. 2009. Utylizacja metanu z pokładów węgla w polskich kopalniach podziemnych. Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków 2009.

PN-EN ISO 14045:2012: Environmental management – Eco--efficiency assessment of product systems – Principles, requirements and guidelines

Buła Z., Jachowicz M., Żaba J., 1997. Principal characteristics of the Upper Silesian Block and Małopolska Block border zone (southern Poland). Geological Magazine, 134, 669-677.

Buła Z., Żaba J., 2008. Structure of the Precambrian basement of the eastern part of the Upper Silesian block (Brunovistulicum). Przegląd Geologiczny, 56, 473-480.

Buła Z., Habryn R., Jachowicz-Zdanowska M., Żaba J. 2015. The Precambrian and Lower Paleozoic of the Brunovistulicum (eastern part of the Upper Silesian Block, southern Poland) - the state of the art. Geological Quarterly 59 (1), 123-134. DOI: https://doi.org/10.7306/gq.1203

Dembowski Z., Kotas A., Malczyk W. 1964. Identyfikacja pokładów węgla w Górnośląskim Zagłębiu Węglowym. Wydawnictwa Geologiczne, Warszawa.

Dembowski Z. 1972. Ogólne dane o Górnośląskim Zagłębiu Węglowym. in: Karbon Górnośląskiego Zagłębia Węglowego. Polish Geological Institute Special Papers, 61, 9-16.

Hanzlik F. 1963. Dokumentacja geologiczna złoża węgla kamiennego kopalni „Wesoła".

Kotas A., Malczyk W. 1972. Górnośląska seria piaskowcowa piętra namuru górnego Górnośląskiego Zagłębia Węglowego. Polish Geological Institute Special Papers, 61, 412-466.

Kotas A. 1985. Uwagi o ewolucji strukturalnej GZW. [In:] Conference Papers. Tektonika GZW. UŚ, Sosnowiec: 17-46.

Lunarzewski L., Battino S. 1983. Prediction of required ventilation levels for longwall mining in Australian gassy coal mines. // AusIMM Illawarra Branch Symposium, Vent of Coal Mines.

Nawrocki J., Poprawa P., 2006. Development of Trans-European Suture Zone in Poland: from Ediacaran rifting to Early Palaeozoic accretion. Geological Quarterly, 50 (1), 59-76.

Prusek S., Krause E., Skiba J. 2020. Designing coal panels in the conditions of associated methane and spontaneous fire hazards, International Journal of Mining Science and Technology 30(4), 525–531. doi: 10.1016/j.ijmst.2020.05.015.

Stankiewicz J. 1955. Dokumentacja geologiczna złoża węgla kamiennego kopalni „Wesoła".

PARTNERS

OIL AND GAS INSTITUTE
– NATIONAL RESEARCH INSTITUTE

CENTRAL MINING INSTITUTE
OF KATOWICE

UNIVERSIDAD DE OVIEDO

IMPERIAL COLLEGE OF SCIENCE
TECHNOLOGY AND MEDICINE

REI INCORPORATION

POLSKA GRUPA GÓRNICZA S.A.