Conducting CMM Project Pre-Feasibility Studies

Training by the U.S. EPA in Support of the Global Methane Initiative (GMI)

Global Methane Initiative

Welcome

The United States Environmental Protection Agency (EPA) developed this course in support of the GMI and in conjunction with the United Nations Economic Commission for Europe (UNECE). What is the GMI?

This course introduces principles for assessing the potential of developing projects to capture and/or use Coal Mine Methane (CMM). The general approach described in the course should be underpinned by mine-specific data and analyses, allowing the principles to be tailored to the unique conditions at each mine. Ideally, such an assessment will lead to project development and implementation.

What Is the Global Methane Initiative?

Global Methane Initiative

The Global Methane Initiative (GMI) is a voluntary, multilateral partnership that aims to reduce methane emissions and to advance the abatement, recovery, and use of methane as a clean energy source.

GMI Partner Countries

GMI Partner Countries account for nearly 70% of total global manmade methane emissions, which is equivalent to approximately 5,000 $MMTCO_2e$.

Conducting CMM Project Pre-Feasibility Studies: Course Modules

Module 1: Introduction and Objectives

Module 2: Mine Background Information and Evaluation

Module 3: Resource Assessment

Module 4: Forecasting Methane Production from Gas Drainage Systems

Module 5: Improvements to Gas Drainage

Module 6: Quantifying the Benefits of Improvements to Methane Drainage Systems

Module 7: Market, Risk, and Financial Analyses

Module 8: Case Study – Liulong Mine, China

Module 8

Case Study - Liulong Mine, China

What You Will Learn

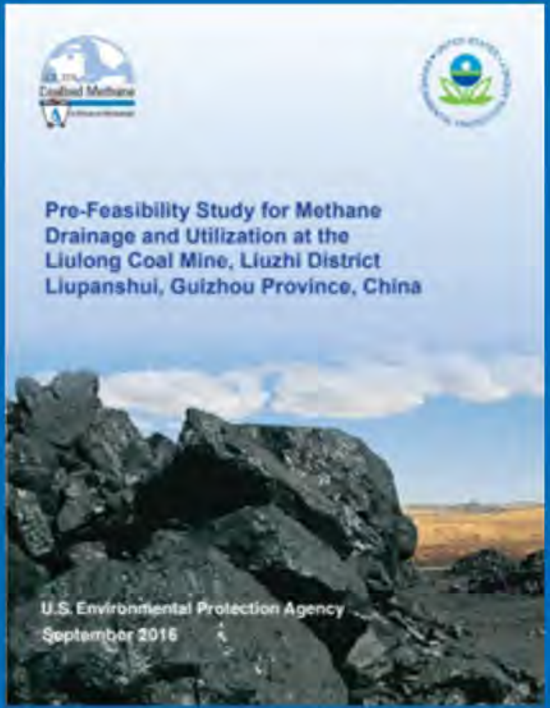
After completing this module, you will understand how the concepts presented in Modules 1 through 7 are applied when conducting a CMM pre-feasibility study.

The outline of this module follows the steps in a pre-feasibility study, as described in the previous modules of this training:

- Background and Mine Evaluation (Module 2)
- Resource Assessment (Module 3)
- Gas Production Forecasting for Methane Drainage Systems (Module 4)
- Improvements to Gas Drainage (Module 5)
- Quantifying Benefits of Improvements (Module 6)
- Market, Financial & Risk Analyses (Module 7)

Time needed to complete this module:

Approximately 60 minutes



Users are encouraged to supplement this training by referencing the detailed pre-feasibility study report that GMI prepared for the Liulong Mine.

Background and Mine Evaluation

Selecting a Study Candidate

On behalf of GMI, EPA has prepared more than 50 pre-feasibility studies in 11 countries to promote methane recovery and use at working underground coal mines.

To select a study candidate, EPA considers the following criteria:

- Is the host country a GMI partner?
- Are there available gas resources at the mine and is there realistic potential for a CMM project?
- Will a successful CMM project serve as a catalyst for additional CMM projects in the region or country of study?
- Does the project have the support of in-country partners?

Candidate Selection

In 2015, EPA agreed with the Baise Mining Group (BMG), a mine owner/operator in China, to conduct a pre-feasibility study for the Liulong Mine in Guizhou Province, China, in support of GMI activities.

Selection of the Liulong Mine

EPA considered the Liulong Mine to be a good candidate for the study because:

- ☑ The Government of China and the Guizhou Provincial Government have made CMM drainage a very high safety priority in the province.
- ☑ The Central Government of China and the Guizhou Provincial Government have placed a high priority on CMM utilization.
- ☑ Regional authorities and the mine owner and operator sought technical assistance.
- ☑ Early development of successful gas drainage and utilization projects can lead to sector-wide growth.
- ☑ Initial efforts at gas capture and use in the current mine working will be expanded to a much larger operation when coal and gas reserves are added through a reserve addition, resulting in greater emission reductions.

Preparing for Initial Data Request

EPA formed a GMI team to conduct the study, which included the China Coal Information Institute (CCII), highlighting the importance of having in-country experts.

To begin, the GMI team submitted an initial data request to BMG to obtain basic information about the mine, including details about the mine owner/operator, mine operations, and methane resources.

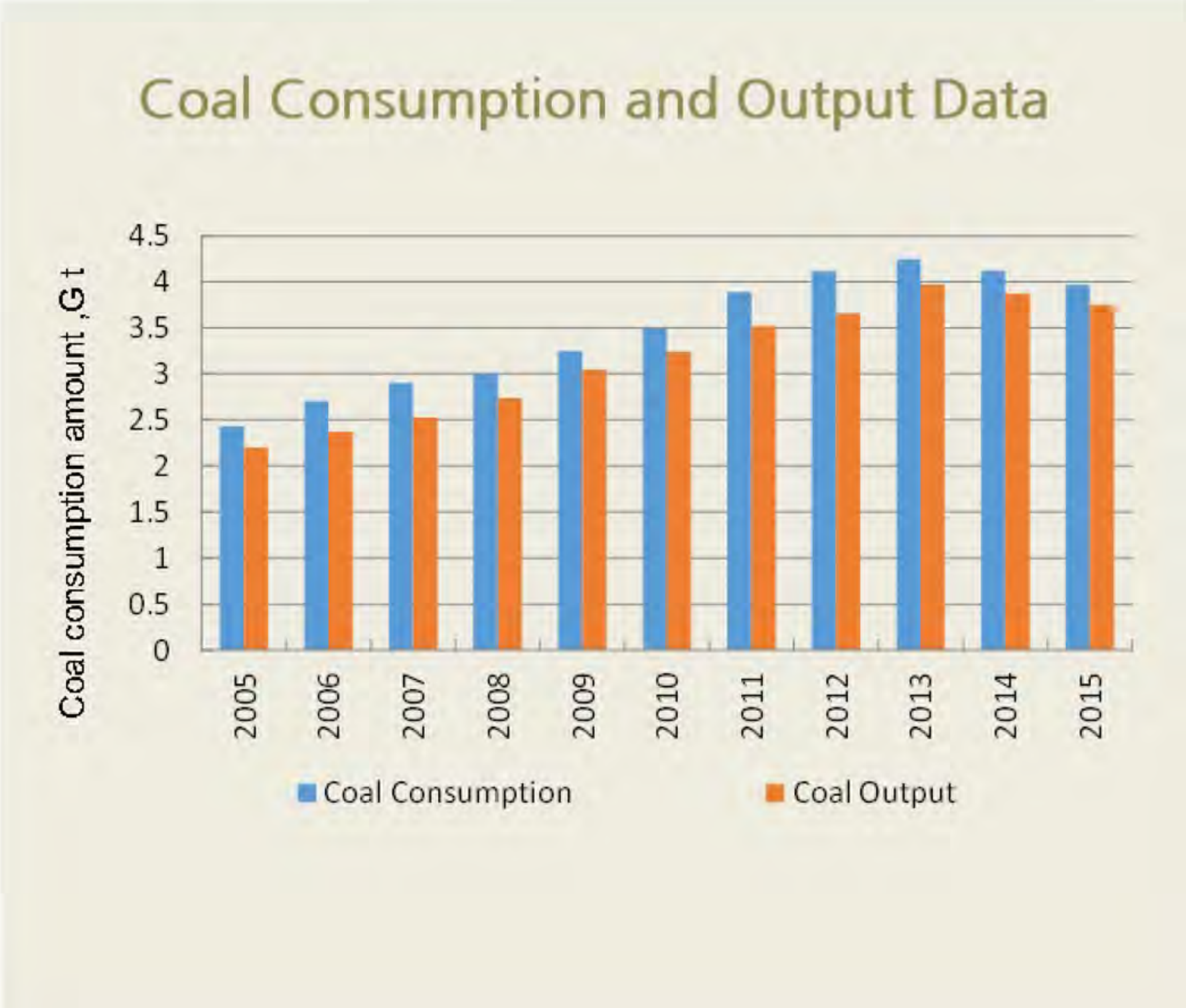
Based on BMG’s responses to the initial data request, the GMI team prepared and sent two additional data requests that facilitated an informed initial evaluation.

Following the initial data requests, EPA and CCII conducted a site visit to the mine to meet with mine management, obtain additional data, and survey the site.

Historical Coal Production in China

The GMI team gathered national data on coal production, coal consumption, and local and national policies in order to:

- Better understand the near-term and longer-term trends in coal production and in the coal sector.
- Assess the overall health of the industry and China's approach to coal production and use.
- Provide a more informed perspective on whether working mines are likely to continue operations sufficient to sustain a CMM project over its life.



Future of Coal Production

The national level overview of coal production and the review of policies showed that, even with declining production and consumption in recent years, annual decreases in production were relatively small and that coal production would continue on a large scale for many years to come.

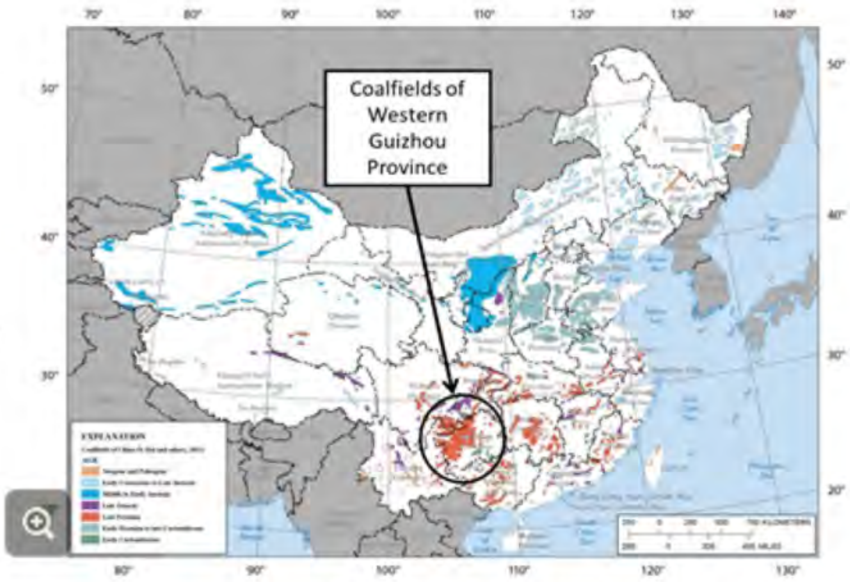
Based on the review, it was determined that it was unlikely that the Liulong Mine would cease production and close due to declining coal demand and/or government policy.

CMM and CBM in the Guizhou Province

The GMI team collected data on regional CMM reserves and current CMM utilization rates and types to understand current trends in the area of the mine.

The data showed:

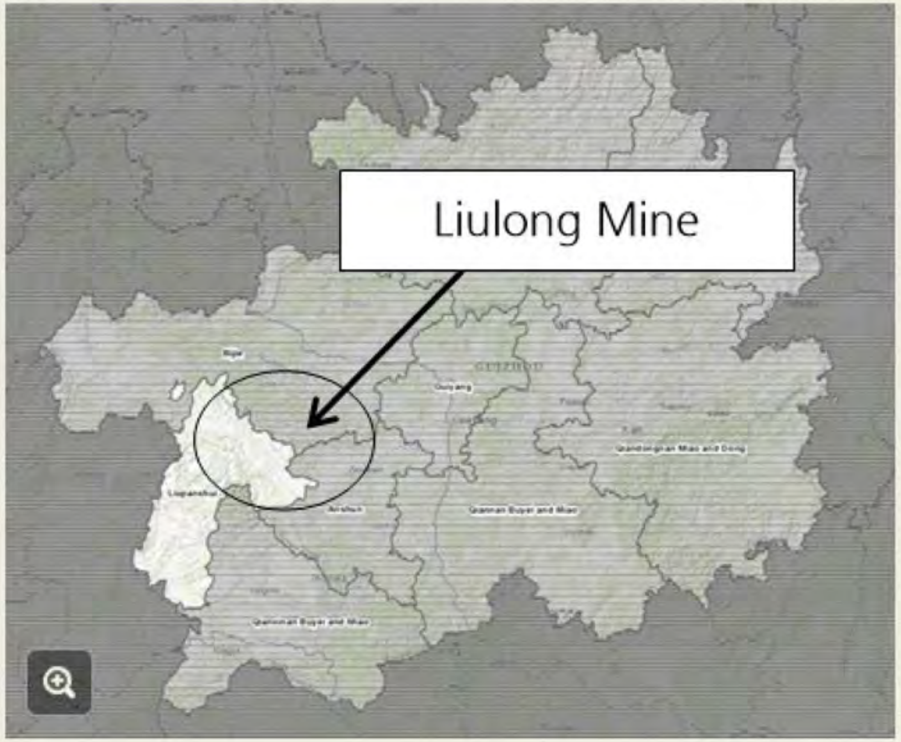
- CMM reserve estimates in Guizhou: **3.15 trillion cubic meters (tcm)**.
- **45%** of the CMM reserves are in the Liupanshui Coalfield, where the Liulong Mine is located.
- Average gas utilization rate: **16%** (typically for power generation/civil use).



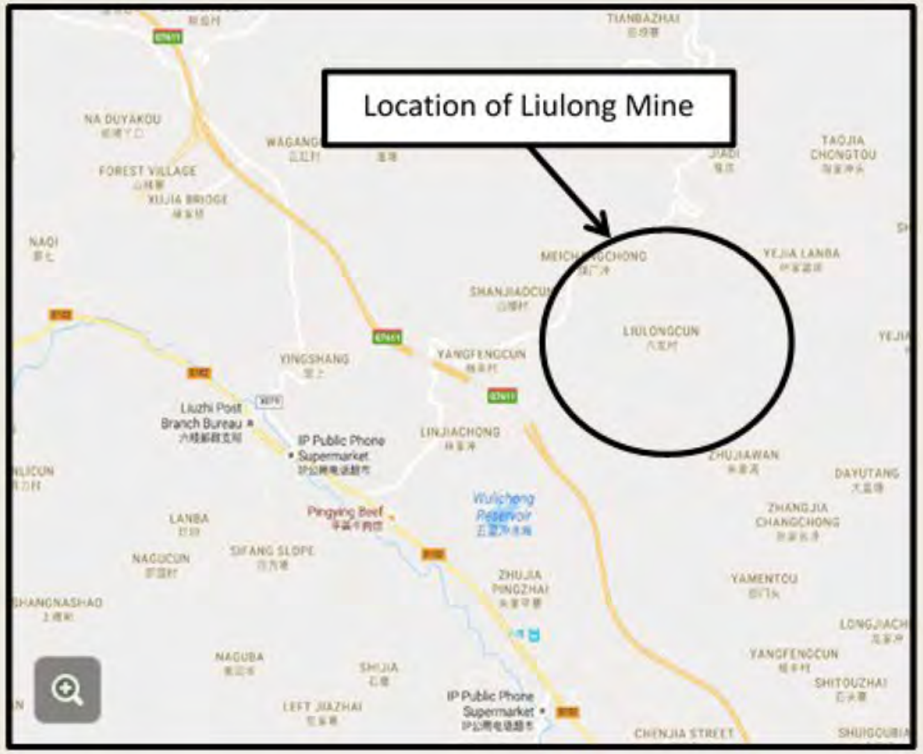
Source: U.S. Geological Survey, 2014

Regional experience with CMM capture and use can increase the odds for successful CMM projects because technical expertise, experience, and equipment are more likely to be available and accessible.

Location of the Liulong Mine



Map of the Guizhou Province highlighting the Liupanshui City



Detailed map of the Liuzhi Special District in Liupanshui City showing the exact location of the mine

Mine Location Details

Next, the GMI team compiled background information on the region, regional economy, topography, meteorological conditions, infrastructure, and the mine's operational facilities. This information helped the team understand local conditions and other factors that might impact CMM capture and utilization.

- The Liuzhi Coalfield is one of the three most productive coalfields in Guizhou Province.
- The mine portal and mine buildings are located in the small village of Mitangtian at an elevation of 1500 m above sea level.
- The mining portal is located 8 km from the Pingzhai Town Government, 8 km from the Liuzhi railway station, and 8 km away from the An-shui highway.
- The existing mine boundary covers 7 square kilometers (km^2) of surface.
- Following a reserve addition, the mine boundaries will cover 45 km^2 of surface.

Liulong Mine Characteristics

The Liulong Mine is located in karst terrain with undulating topography on the surface and caves and other void spaces below the surface in limestone formations. The mine was classified by regulatory authorities as a coal and gas outburst mine.

The mine obtained a license to produce up to 600,000 tonnes per annum (tpa) of coal and operated in 2 worked seams: No. 3 and No. 7 coal seams.

There is no existing CMM use.

Coal reserves include:

- Total reserves: 6.8 million tonnes (Mt)
- Recoverable reserves: 5.1 Mt

Gas drainage system characteristics include:

- CH_4 flow in gas drainage: 160 -763 cubic meters per hour (m^3/hour)

Reserve addition (Dayong field): +75 Mt

After Dayong addition: Expected production was 1.5 million tpa.

Mine Owner: BMG

A pre-feasibility study should include information about the owner/operator, including details about the corporate structure and operations, financial position, CMM experience, and reputation, because the owner/operator is typically a primary stakeholder in the project.

The owner/operator's capacity and interest in supporting the project are essential to project success.

The GMI team obtained background information about the BMG, who is the owner/operator of the Liulong Mine. The information was provided by BMG but was also accessed from other public sources.

Profile of the BMG

The Liulong Mine was privately owned until 2014, when the BMG purchased a majority share.

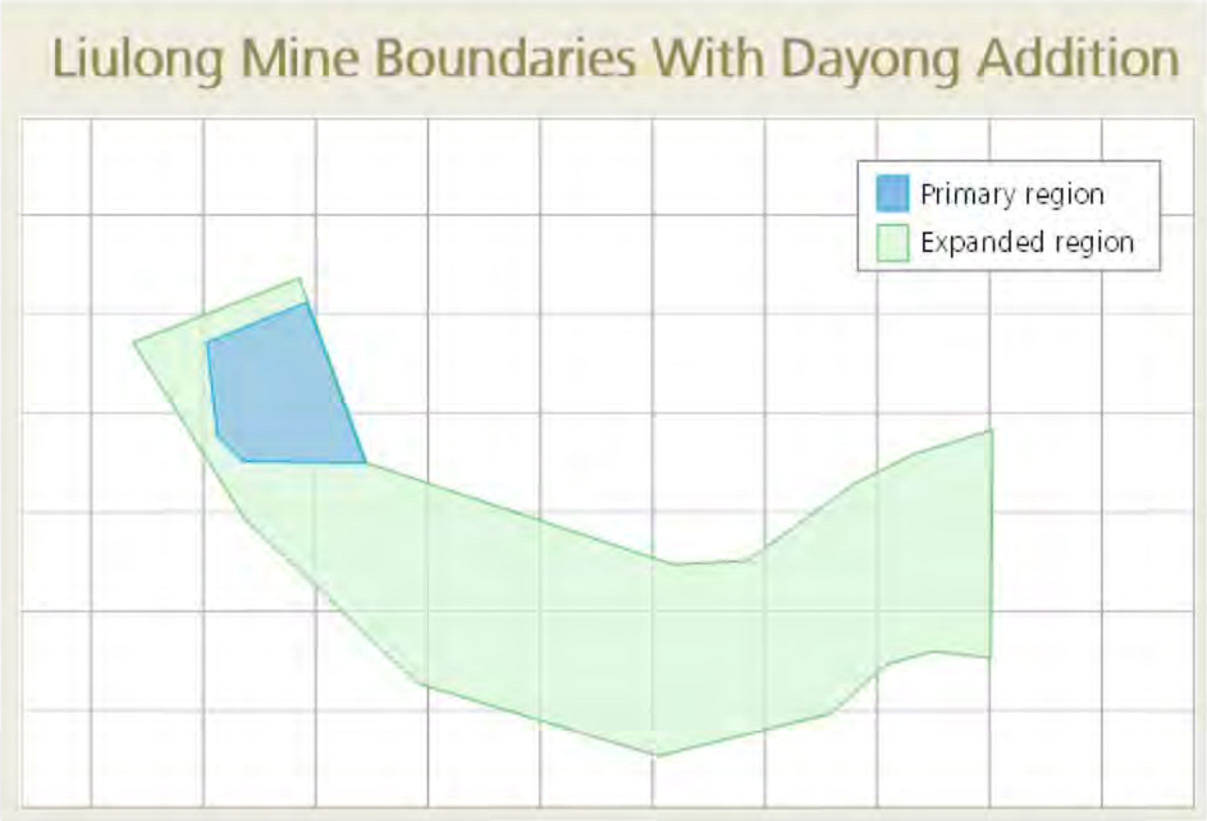
BMG Company Profile

- State Owned Enterprise in Guangxi
- Assets = CNY 8 billion (USD 1.2 billion)
- 22 enterprises in multiple industries
- Liulong Mine is BMG's 1st investment in Guizhou
- Liulong Mine is BMG's 1st gassy mine

Notable Changes to Mining Operations

At this stage, it was important to note any changes to mine operations that may impact CMM production. For example, during the data request and mine visit, the GMI team learned that BMG was planning a significant reserve addition to the Liulong Mine.

- The mine was planning to add coal and gas reserves by acquiring the adjoining Dayong coalfield.
- As a result of acquisition, coal reserves were going to increase by 75 Mt.
- Annual coal production would increase to 1.5 Mt per year.
- The reserve addition was scheduled to occur in 2018 and would directly impact the planned project.



Resource Assessment

Evaluating CMM Resources at the Liulong Coal Mine

BMG provided data on coal seams and original gas content, which allowed the GMI team to evaluate CMM resources. The table below summarizes the data provided:

Reported Gas Content of the Coal Seams in the Existing Mining Area (m^3/t)

Coal Seam	No.3	No. 7	No. 18*
Original gas content (m^3/t)	12.63	15.06	15.62

*Seam 18 is permitted for mining, but is not being currently mined

The pre-feasibility study report, available on the GMI website, includes additional details about the basin and site geology. Data provided by BMG showed that:

- Gas content and seam thickness were uniform through the existing mine and the Dayong addition.
- The addition of the Dayong coalfield reserve increased methane resources by 2 billion m^3.

Liulong Mine CMM Emissions in 2014

BMG provided the following 2014 CMM emissions statistics for the Liulong mine:

- **Gas drainage volume**: 2.76 Mm^3
- **Methane concentration range**: 8% to 30%
- **Average methane concentration**: 21%

The table below shows reported relative emissions (m^3/tonne of coal mined) and absolute emissions (m^3/min) at the Liulong Mine in 2014.

Coal Seam No.	Working face gas emission rate (m^3/t)		Tunneling gas emission rate (m^3/min)		Gas emission rate in the mining area (m^3/t)	Gas emission rate in the mine	
	q_1	q_2	q_3	q_4		Specific emissions (m^3/t)	Absolute emissions (m^3/min)
3	10.2	21.9	0.66	1.04	37.65	56.47	36.65
7	7.73	0.00	3.50	1.30	25.75	38.63	24.39

Historical Liulong Mine CMM Emissions

BMG could not provide extensive historic data on CMM emissions. However, in this case, the multi-year historic data would offer only limited insight because of the recent increase in coal production capacity.

- In 2015, coal production capacity increased from 150,000 tpa to 600,000 tpa.
- In 2016, a new working face increased gas production to 500,000 m^3 per month, effectively doubling the volume of CMM produced.

Current Gas Drainage Practices at the Liulong Mine

The mine relied on drainage practices that were characterized as short cross-panel boreholes and were known to have the following issues:

- Problems with borehole stability
- Wide range of gas flow
- Low methane concentration
- Limited data availability

Mine Gas Drainage System

The principal components of the mine's gas drainage system were:

Two 2BEC-420 high negative pressure drainage pumps

- 160 kW of motor power
- Maximum pressure of 16,000 Pa

Two 2BEA-303 low negative pressure drainage pumps

- 75 kW of motor power
- Maximum pressure of 3,300 Pa

400 mm high negative pressure pipe

- Travels from the exhaust rise to a horizontal level of 1,350 m above sea level and to the drive surfaces

400 mm low negative pressure pipe

- Placement in the exhaust airway at the surface with an elevation of 1,033 m above sea level

The GMI team was unable to visit and inspect the pump station during the mine visit because it was under repair.

The photo above shows a typical pump station at a Chinese mine.

CMM Monitoring System at the Liulong Mine

The coal mine installed a sophisticated KJ90NB CMM monitoring system, which is comprised of two dedicated monitoring computers, along with one standby KJ90NA system.

The system includes gas sensors, negative pressure transducers, equipment on/off transducers, air velocity transducers, and water level sensors that provide mine staff with real-time continuous monitoring.

CMM Monitoring System Control Room

Mine employees continuously monitored air flow and methane concentration data in a central control room.

In addition to monitors at staff desks, the control room contained a large common screen providing live underground camera feeds, staff positions throughout the mine in real time, and continually updated data on methane concentration and airflow measurements throughout the mine.

Alarms are triggered for any measurements outside of expected ranges.

Improvements to Gas Drainage

Gas Drainage Options Considered by BMG Before the GMI Team Prepared the Pre-feasibility Study

BMG had previously evaluated two options for improving gas drainage at the Liulong Mine before the pre-feasibility study.

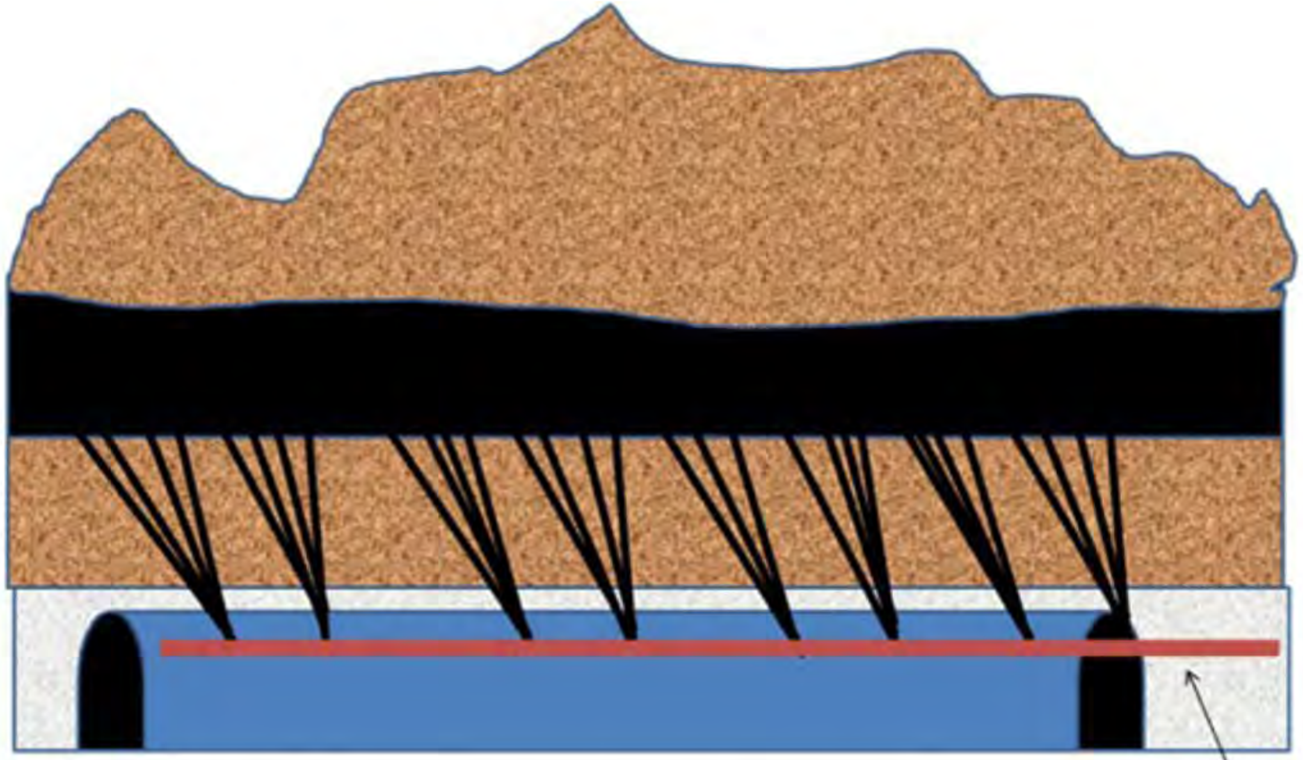
At the time of the study, BMG had not attempted to implement either drainage option.

The two options the mine considered previously had the following limitations:

1. **In-seam boreholes drilled vertically from an underlying rock gallery**
   - Were attempted at several mines in the Ghuizhou Province
   - Were technically challenging
   - Tend to be very expensive
2. **Surface vertical pre-drainage boreholes**
   - BMG was allowed to drill boreholes from the surface for mine safety reasons
   - BMG did not own rights to produce gas at the surface for utilization
   - Royalties were due to the holder of mineral rights for any gas produced and used 5 years after a surface borehole was drilled

Improvement Option #1 Considered by the Mine Prior to the Study

Vertical boreholes drilled upward from an underlying rock gallery are not commonly used. Therefore, the GMI team developed a schematic for the pre-feasibility report to help users better understand this method, which has been attempted at some mines in the Guizhou Province.



Gallery driven in limestone below the mined seam to drill cross measure boreholes upward into the seam for in-mine pre-drainage

GMI Systematic Approach to Identify the Preferred Solution to Improve Gas Drainage at the Liulong Mine

Based on data provided by the mine, the GMI team proposed a systematic approach to:

1. Identify alternative approaches to improve mine gas drainage using improved borehole design.
2. Specify technically feasible options within each alternative approach for further evaluation.
3. Develop estimates of gas production for each option using numerical modeling for pre-mine drainage boreholes and engineering equations for gob gas boreholes.
4. Distill the list of technically feasible options to the three best solutions to improve gas drainage.
5. Perform a risk assessment, market analysis, and financial analysis of the three potential solutions to identify the optimal solution.

GMI Proposal to Improve Mine Gas Drainage

Following discussions with BMG and the evaluation of operational and geologic data at the Liulong Mine, the GMI team identified two alternatives to improve gas drainage at the mine.

Gas Drainage Improvement Alternative #1	Gas Drainage Improvement Alternative #2
Directionally drilled horizontal in-seam boreholes drilled from the underlying rock gallery below the mined seam.	Directionally drilled horizontal gob boreholes drilled into the rock above the mined seam.

These alternatives had not been considered before because:

- The mine's coal production and production rates had not warranted more technically advanced alternatives using directional drilling.
- There was limited experience and expertise in China using these methods.

Alternative #1: Steps to Evaluate Directionally Drilled In-Seam Boreholes

Steps to evaluate directionally drilled in-seam boreholes included:

1. Define uniform longwall dimensions in the No. 3 and No. 7 seams for numerical modeling.
2. Establish borehole spacings of 10 m and 30 m in the model longwall panel in each seam, thus establishing four options for Alternative #1: in-seam directionally drilled boreholes.
3. Run numerical simulations to project the reduction in gas pressure in the model panel for each option.
4. Model gas production rates and cumulative gas production for individual boreholes. The production rates for individual boreholes will be used later to forecast mine-wide gas production for the life of the project.

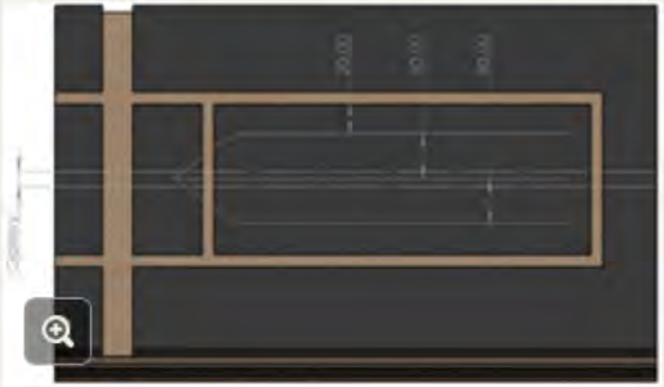
Alternative #1: In-seam Boreholes

In-seam boreholes would be implemented from the rock gallery penetrating into the mining seam at intervals of 30 m and 10 m.

This approach:

- ✓ Provides additional reach
- ✓ Mitigates underlying drainage galleries
- ✓ Enables more drainage time

In-seam borehole plan view showing distance between boreholes (30 m between laterals, and 20 m between 1st lateral and tailgate)



In-seam borehole profile view (30 m borehole penetration into the seam from each lateral)

Alternative #2: Steps to Evaluate Directionally Drilled Horizontal Gob Boreholes

Steps to evaluate directionally drilled horizontal gob boreholes included:

1. Define uniform longwall dimensions in the No. 3 and No. 7 seams.
2. Establish location in gate roads or main entries from which boreholes will be drilled and wellhead will be placed in each seam.
3. Determine borehole height and length over mined panel for each borehole.
4. Define three borehole diameters and two vacuum pressures which will be used in an engineering equation to estimate gas production from the boreholes. With two seams, this results in 12 cases for Alternative #2.

Alternative #2: Horizontal Gob (Goaf) Boreholes

Three horizontal gob boreholes (HGB) proposed at varying heights on the up-dip side of the panels along the return airway.

In this approach, drilling can originate out of:

- The gate roads
- Mains

This approach provides:

✓ Potential for higher rates of gas capture

✓ Greater borehole stability

Evaluation of Proposed Alternatives to Improve Gas Drainage

To assess the two proposed improvements to gas drainage, the GMI team defined specific options for each alternative that would be subject to further review. The GMI team determined parameters for each option based on:

- Operating conditions at the Liulong Mine.
- Experience designing and modeling in-seam and horizontal gob boreholes at other mines in China and in other countries with similar conditions.
- Experience drilling in-seam and horizontal gob boreholes and installing, operating, and evaluating gas drainage systems.

Click the buttons to view details about the options for each improvement alternative.

Improvement Alternative #1
In-seam boreholes
4 options

Improvement Alternative #2
Horizontal gob boreholes
12 options

Proposed Improvements: Options Evaluated for Alternative #1

Improvement Alternative #1: In-seam boreholes				
	Seam		Borehole penetration	
	No. 3	No. 7	30 m spacing	10 m spacing
Option 1	•		•	
Option 2		•	•	
Option 3	•			•
Option 4		•		•

Proposed Improvements: Options Evaluated for Alternative #2

Improvement Alternative #2: Horizontal gob boreholes							
	Seam		Vacuum Pressure		Borehole diameter		
	No. 3	No. 7	Low	High	96 mm	121 mm	146 mm
Option 1	•		•		•		
Option 2	•		•			•	
Option 3	•		•				•
Option 4	•			•	•		
Option 5	•			•		•	
Option 6	•			•			•
Option 7		•	•		•		
Option 8		•	•			•	
Option 9		•	•				•
Option 10		•		•	•		
Option 11		•		•		•	
Option 12		•		•			•

Predicting Gas Production from Boreholes

The GMI team used different approaches to predict gas production from boreholes for the two improvement alternatives to current gas drainage practices.

Improvement Alternative #1
In-seam boreholes

- For this pre-feasibility study, numerical modeling in the form of a reservoir simulation was used to simulate gas production from in-seam boreholes.
- Reservoir simulations can be used for in-seam boreholes whether the boreholes are drilled vertically or horizontally.
- To perform the simulation, the GMI team used a commercially available reservoir simulation software package developed for unconventional gas reservoirs including coal seams.

Improvement Alternative #2
Horizontal gob boreholes

- Recognized engineering equations were used to predict gas flows from gob boreholes.

Improvement Alternative #1

Alternative #1: Use Numerical Modeling

Specific data are required to run the numerical model. The more complete the dataset is, the more likely it is that the model will provide accurate results.

- Where possible, mine-specific data were used, but it was necessary to use proxy data for some inputs.
- The GMI team constructed a series of reservoir models designed to simulate gas production volumes from in-seam pre-drainage boreholes.

The most important model inputs, noted in Module 4, were:

- ✓ Seam thickness
- ✓ Gas content
- ✓ Permeability
- ✓ Isotherms
- ✓ Porosity
- ✓ Pressure

Click the button to view a table of example data inputs for the numerical model.

Example Numerical Modeling Data Inputs

Example Numerical Modeling Data Inputs

Reservoir Parameter	Value(s)		Notes
	Seam 3	Seam 7	
Seam Elevation (TOP), m above MSL	1496	1420	Mine data from Area 1; Core hole No. 24
Coal Depth (TOP), m	80	149	Mine data from Area 1; Core hole No. 24
Coal Thickness, m	1.3	8.0	Mine data from Area 1; Core hole No. 24
Coal Density, g/cc	1.62	1.39	Mine data
Pressure Gradient, kPa/m^3	11.94	9.51	Calculated from reservoir pressure and depth
Initial Reservoir Pressure, kPa	950	1420	Mine data; Top of each seam
Initial Water Saturation, percent	100	100	Assumption
Langmuir Volume, m^3/tonne	28.97	28.15	Mine data; Isotherm analysis
Langmuir Pressure, kPa	1126	1045	Mine data; Isotherm analysis
In Situ Gas Content, m^3/tonne	12.63	15.06	Mine data
Desorption Pressure, kPa	870	1202	Calculated based on in situ gas content and maximum storage capacity from isotherm

Numerical Modeling of Borehole Spacing

For Improvement Alternative #1, the GMI team evaluated gas production for two mined seams, Seam No. 3 and Seam No. 7, considering two different borehole spacing approaches within each mined seam (10 m and 30 m spacings).

This was required to estimate gas production for four possible options that were then later used to forecast mine-wide gas production.

Alternative #1, Option 1	Alternative #1, Option 2	Alternative #1, Option 3	Alternative #1, Option 4
In-seam boreholes in seam **No. 3** would be drilled horizontally from the underlying rock gallery (or other lower elevation gallery) and penetrate up into the mining seam at intervals of **30 m**.	In-seam boreholes in seam **No. 7** would be drilled horizontally from the underlying rock gallery (or other lower elevation gallery) and penetrate up into the mining seam at intervals of **30 m**.	In-seam boreholes in seam **No. 3** would be drilled horizontally from the underlying rock gallery (or other lower elevation gallery) and penetrate up into the mining seam at intervals of **10 m**.	In-seam boreholes in seam **No. 7** would be drilled horizontally from the underlying rock gallery (or other lower elevation gallery) and penetrate up into the mining seam at intervals of **10 m**.

Numerical Modeling of Borehole Spacing Results

The purpose of developing the four options was to determine if tighter spacings would result in an appreciable increase in gas production from in-seam boreholes.

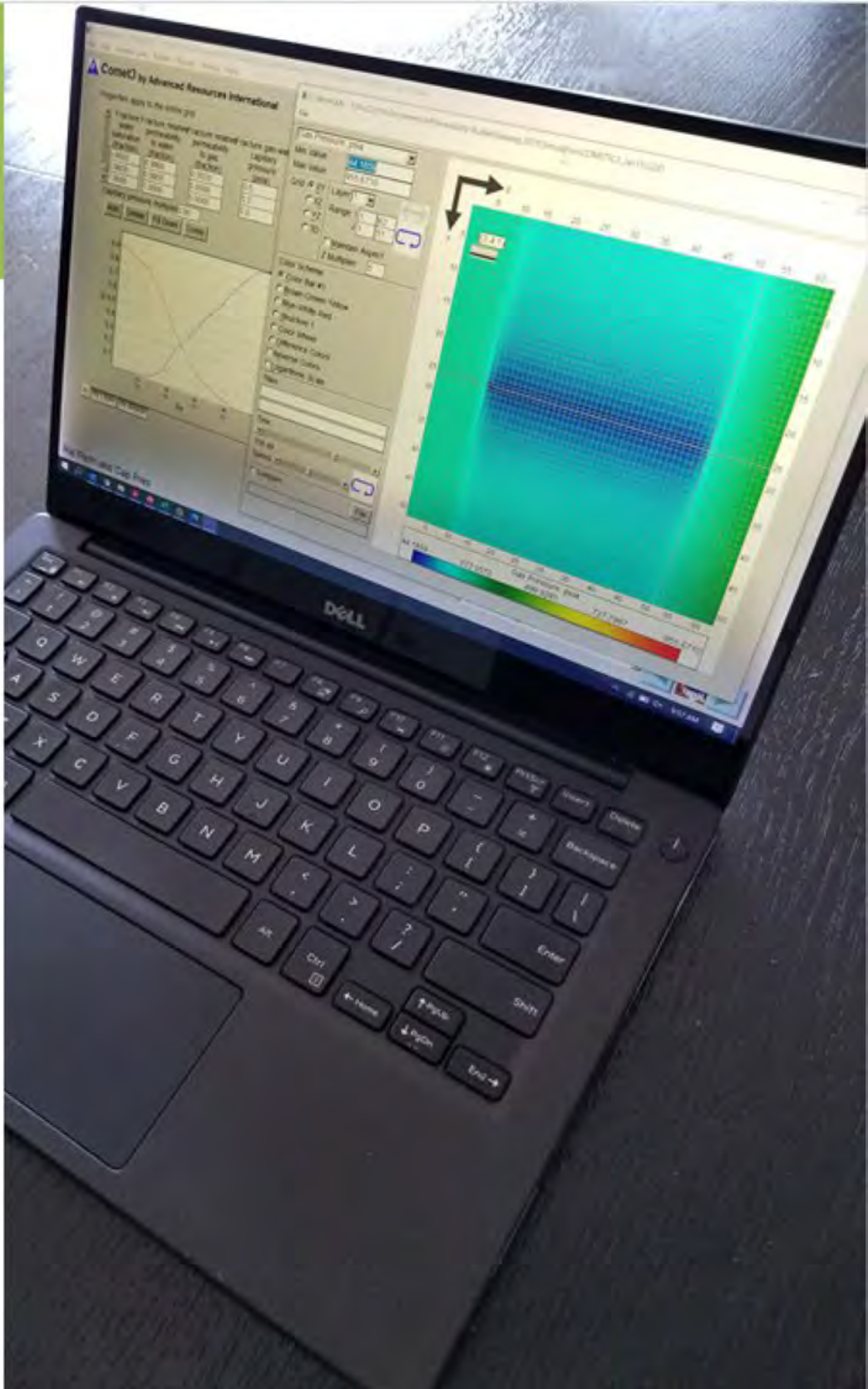
According to the options, all boreholes were to be drilled into a longwall panel with the face dipping at an angle of 29 degrees and were assumed to be 250 m in lateral length.

Numerical Modeling of Longwall Panel Dimensions

Based on the mine plans provided by BMG, the GMI team created standardized dimensions for future longwall panels targeting seams No. 3 and No. 7 for the purposes of modeling gas production rates.

The GMI team used a standard longwall panel with a width of 100 m and a length of 250 m covering an aerial extent of 2.5 hectare (ha).

The models were run to simulate gas production rates and cumulative production volumes from each seam within a typical longwall panel in the current mining area over a 10-year period.



Evaluating Impact of Borehole Spacing

To evaluate the impact of spacing on gas production, the GMI team compared the impact of different 30 m and 10 m borehole spacing on reservoir pressure.

It was necessary for the reservoir simulation to establish a uniform longwall panel so that the team could compare the results from different borehole spacing patterns and extrapolate those to the entire mine.

- Uniform longwall dimensions (100 m x 250 m for this study).
- Reservoir simulation models the production of gas from the coal seam only; it normally does not consider gas resources from adjacent rock strata unless those resources are significant.
- In the case of the Liulong Mine, the gas resources were concentrated in the No.3 and No. 7 seams.

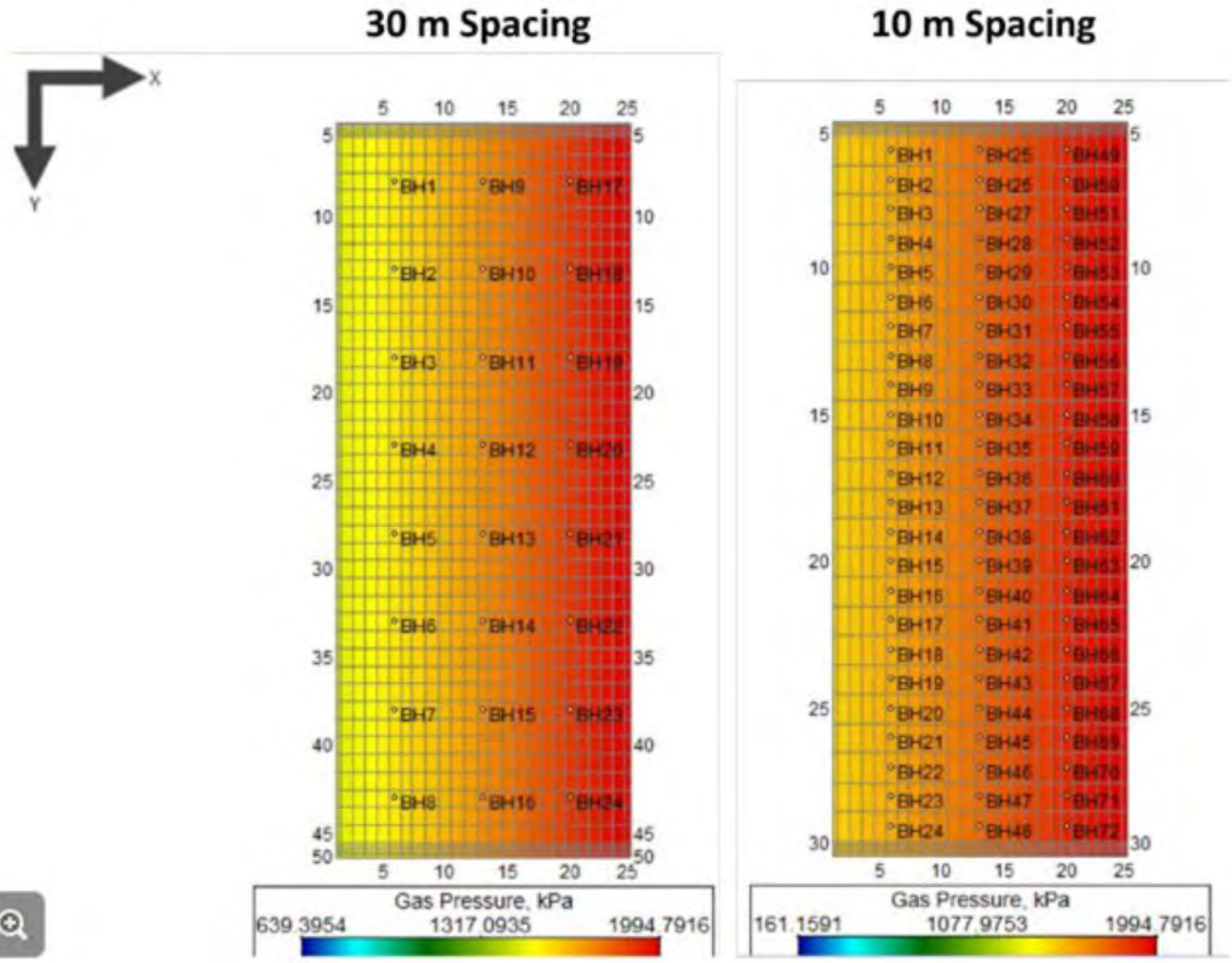
Option Layout

The reservoir simulation uses a grid pattern for borehole location.

Boreholes were spaced at 30 m and 10 m intervals:

- Example No. 7 seam: 30 m spacing (Option 2)
- Example No. 3 seam: 10 m spacing (Option 3)

Planview of Longwall Panel



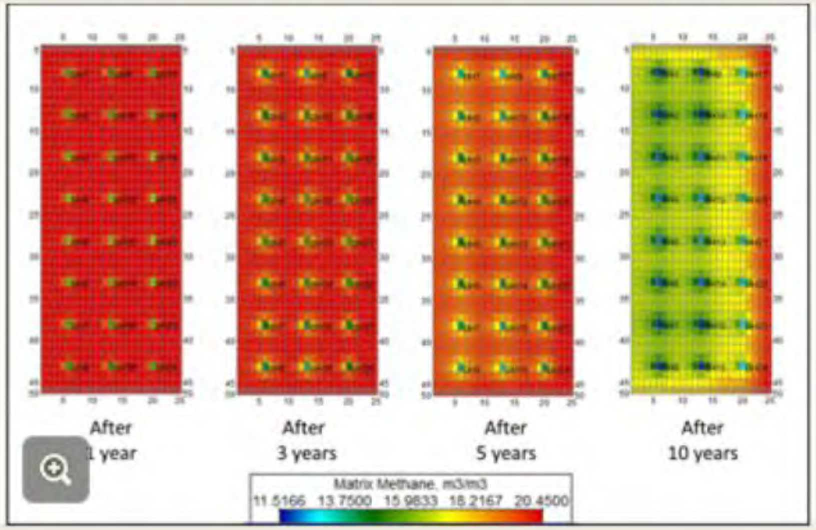
No. 7 Seam

No. 3 Seam

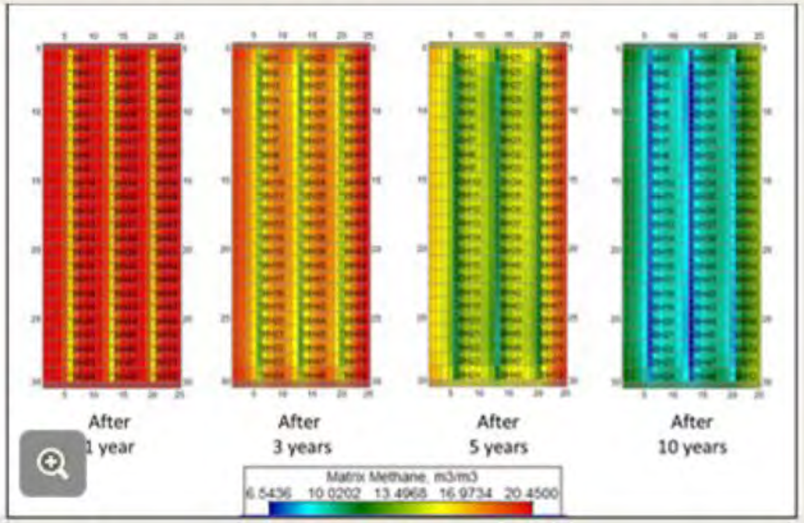
Modeling Reduction in Reservoir Gas Pressure: No. 3 Seam

Next, the GMI team evaluated the impact of gas production in the longwall panel over time:

- No.3 Seam: Impact of gas production on gas pressure in the No. 3 seam in years 1, 3, 5 and 10
- Heat map output: Reduction in in-situ gas content over time; Red (high) to blue (low)



No. 3 Seam – 30 m spacing (i.e., Option 1)

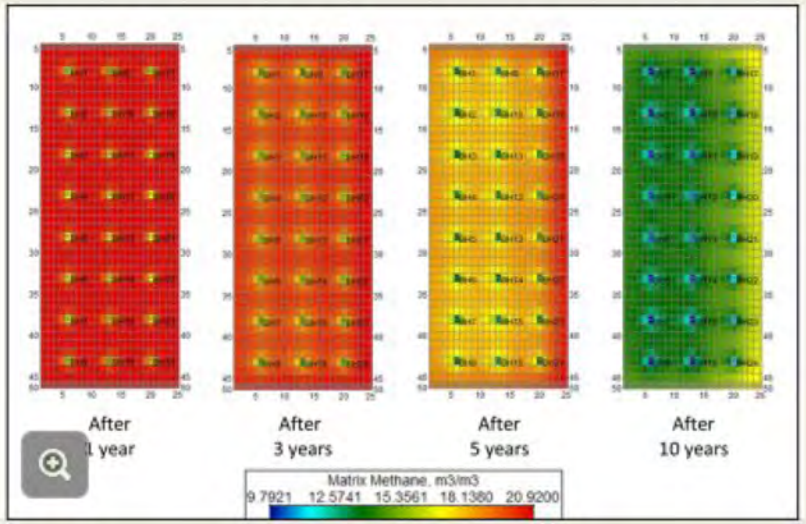


No. 3 Seam – 10 m spacing (i.e., Option 3)

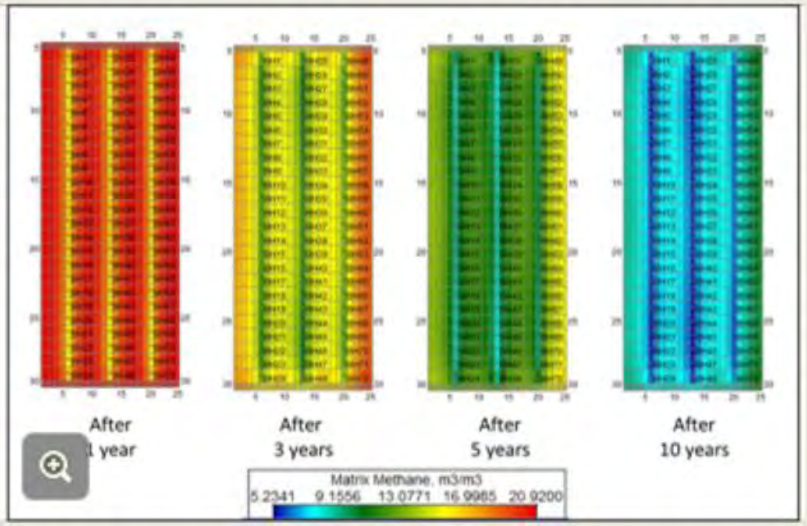
Modeling Reduction in Reservoir Gas Pressure: No. 7 Seam

The GMI team performed the same simulation for the No. 7 seam:

- No.7 Seam: Impact of gas production on gas pressure in the No. 7 seam in years 1, 3, 5 and 10
- Heat map output: Reduction in in-situ gas content over time; Red (high) to blue (low)



No. 7 Seam – 30 m spacing (i.e., Option 2)



No. 7 Seam – 10 m spacing (i.e., Option 4)

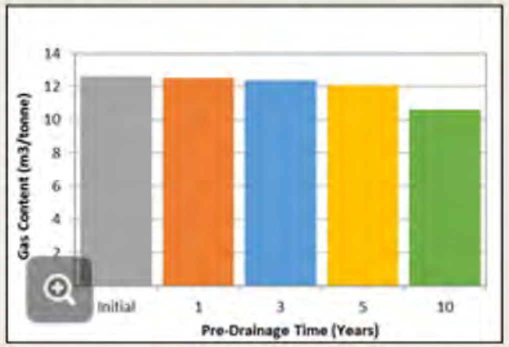
Modeling Residual Gas Content

Another way to assess the effectiveness of the in-seam borehole patterns in seams No. 3 and No. 7 was to compare gas content in the longwall panels over time.

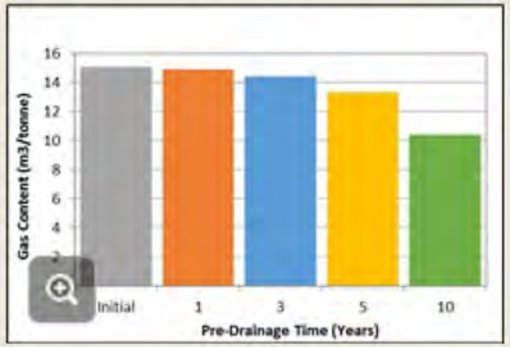
The charts on this slide show reduction in gas content for each option over 1, 3, 5 and 10 years.

It was clear from the charts that 10 m spacing would have a significant impact in reducing gas content, especially in the No. 3 seam. The GMI team performed the same simulation for the No. 7 seam.

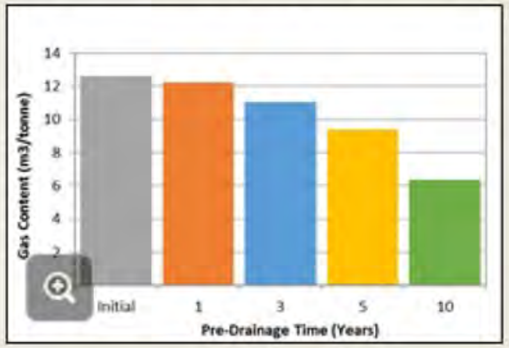
No. 3 Seam at 30 m Spacing (Option 1)



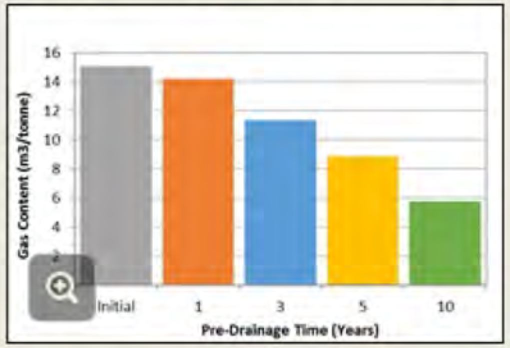
No. 7 Seam at 30 m Spacing (Option 2)



No. 3 Seam at 10 m Spacing (Option 3)



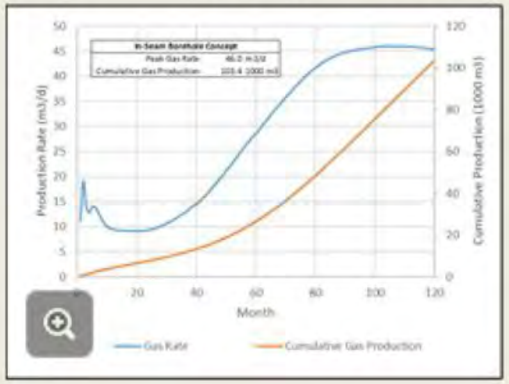
No. 7 Seam at 10 m Spacing (Option 4)



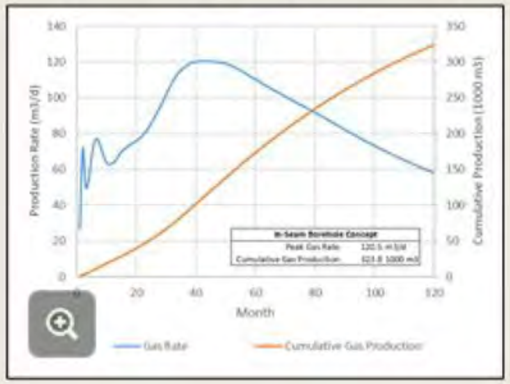
Modeling Gas Production Rate and Cumulative Gas Production

The GMI team also used reservoir simulation to model panel gas production rates and cumulative gas production under the different implementation paths for in-seam boreholes.

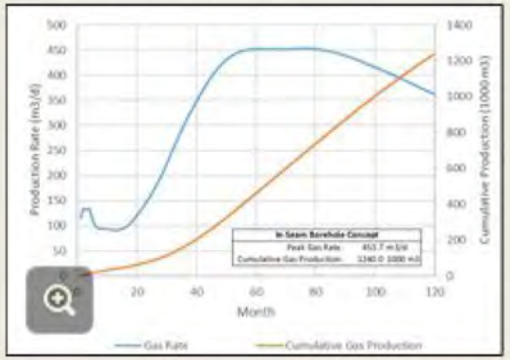
No. 3 Seam at 30 m Spacing (Option 1)



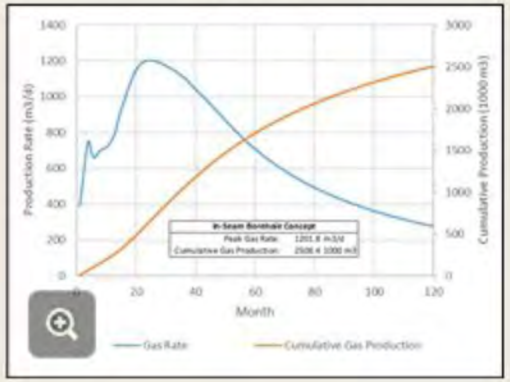
No. 7 Seam at 30 m Spacing (Option 2)



No. 3 Seam at 10 m Spacing (Option 3)



No. 7 Seam at 10 m Spacing (Option 4)



Proposed Improvement Alternative #1 Results

The modeling showed that the optimal technical solution for implementing Alternative #1 was to drill in-seam boreholes spacing them at 10 m in Seam No. 3 (Option 3) and Seam No. 7 (Option 4), which would result in higher gas production and a much greater reduction of in-situ gas content in the longwall panel over time.

Although this was the best technical solution, project feasibility also depends on the financial returns. Spacing borehole penetration every 10 m is more expensive than 30 m spacings.

The financial analysis would evaluate whether the benefit of additional gas production outweighs the cost of drilling additional boreholes for the 10 m spacing option versus the 30 m spacing option.

Improvement Alternative #2

Alternative #2: Horizontal Gob (Goaf) Boreholes

Estimating gas production from HGBs can be challenging since gob gas flow rates typically fluctuate over time and vary with borehole length and configuration.

HGB gas flow rates are most influenced by:

- Borehole diameter
- Borehole length
- Wellhead vacuum pressure
- Reservoir pressure contribution

Gob gas flow rate can be approximated using the General Flow Equation, an engineering equation for the steady-state isothermal flow in a gas pipeline which relates the pressure drop along a pipeline with flow rate.

Engineering Equation for Alternative #2

For this study, the GMI team used the basic equation for steady-state isothermal flow in a gas pipeline, as recommended by E. Shashi Menon, to predict gob gas flow rates.

$$Q = 1.3303\,(10)^{-5}\left(\frac{T_b}{P_b}\right)\left[\frac{(P_1^2 - P_2^2)}{GT_fLZf}\right]^{0.5} D^{2.5}$$

Where:

Q = gas flow rate, measured at standard conditions, l/s
f = coefficient of friction, dimensionless
P_b = base (standard) pressure, kPa
T_b = base (standard) temperature, K
P_1 = upstream pressure, kPa
P_2 = downstream pressure, kPa
G = gas gravity (air = 1.0)
T_f = average gas flowing temperature, K
L = pipe length, km
Z = gas compressibility factor, dimensionless
D = pipe inside diameter, mm

Source: Menon, S. E. (2005). Gas Pipeline Hydraulics. Boca Raton, FL: Taylor & Francis Group, LLC.

Equation Inputs

Inputs for the engineering equation were derived from:

- Mine-specific values provided by BMG
- Proxy values based on industry experience

Methane concentration in the gob gas was assumed to be 70%:

- Modeled methane concentration was much higher than existing methane concentration due to expected improvements in gob gas recovery from installing HGBs

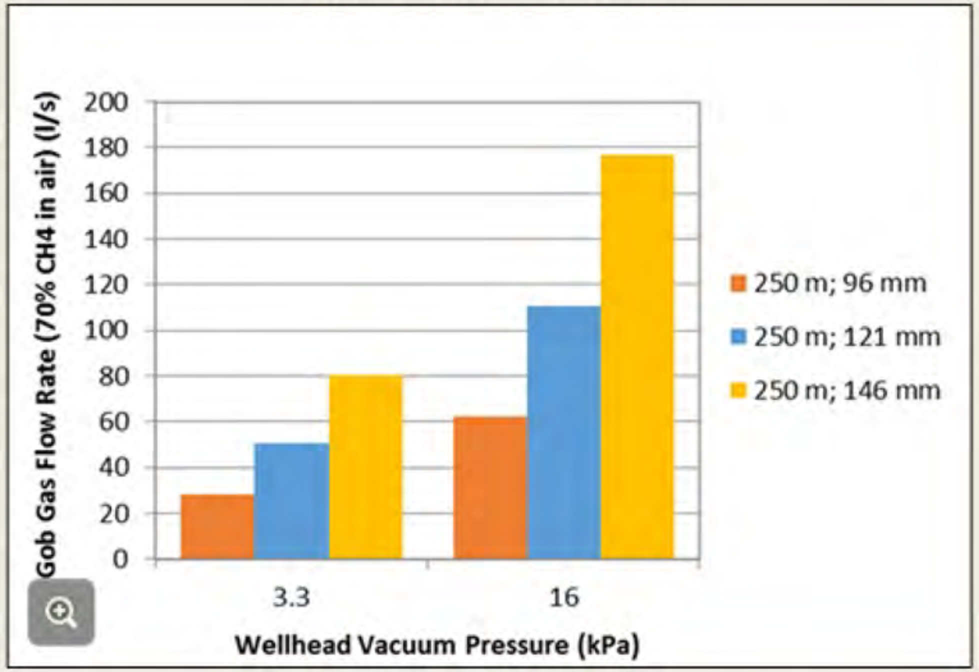
For each seam, 12 options were developed for gas drainage Alternative #2 (six for each seam)

- 3 pipe diameters: 96 mm, 121 mm, and 146 mm
- 2 vacuum pressures: low vacuum (3.3 kPa) and high vacuum (16 kPa)

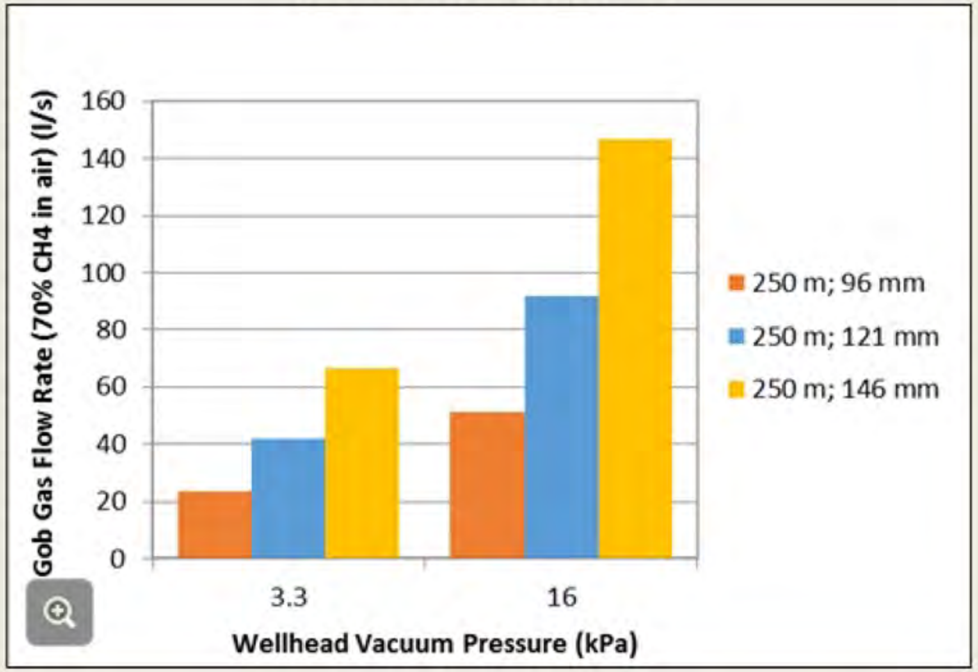
Parameter	Value
Coefficient of Friction, dimensionless	0.0200
Base (standard) Pressure, kPa	No. 3 Seam: 1179 No. 7 Seam: 1729
Base (standard) Temperature, K	293
Upstream Pressure, kPa	No. 3 Seam: 1179 No. 7 Seam: 1729
Downstream Pressure, kPa	Calculated based on wellhead vacuum pressure; 3.3 and 16 kPa options investigated
Gas Gravity (air = 1.0)	0.6
Average Gas Flowing Temperature, K	293
Pipeline Length, km	0.25
Gas Compressibility Factor, dimensionless	Seam No. 3: 0.99 Seam No. 7: 0.98
Pipe Inside Diameter, mm	96, 121 and 146 mm options investigated

Calculated Gob Gas Flow Rates

Gob gas flow rates were projected for 250 m horizontal gob borehole configurations in the No. 3 seam at low pressure and high pressure wellhead vacuum.



Gob gas flow rates were projected for 250 m horizontal gob borehole configurations in the No. 7 seam at low pressure and high pressure wellhead vacuum.



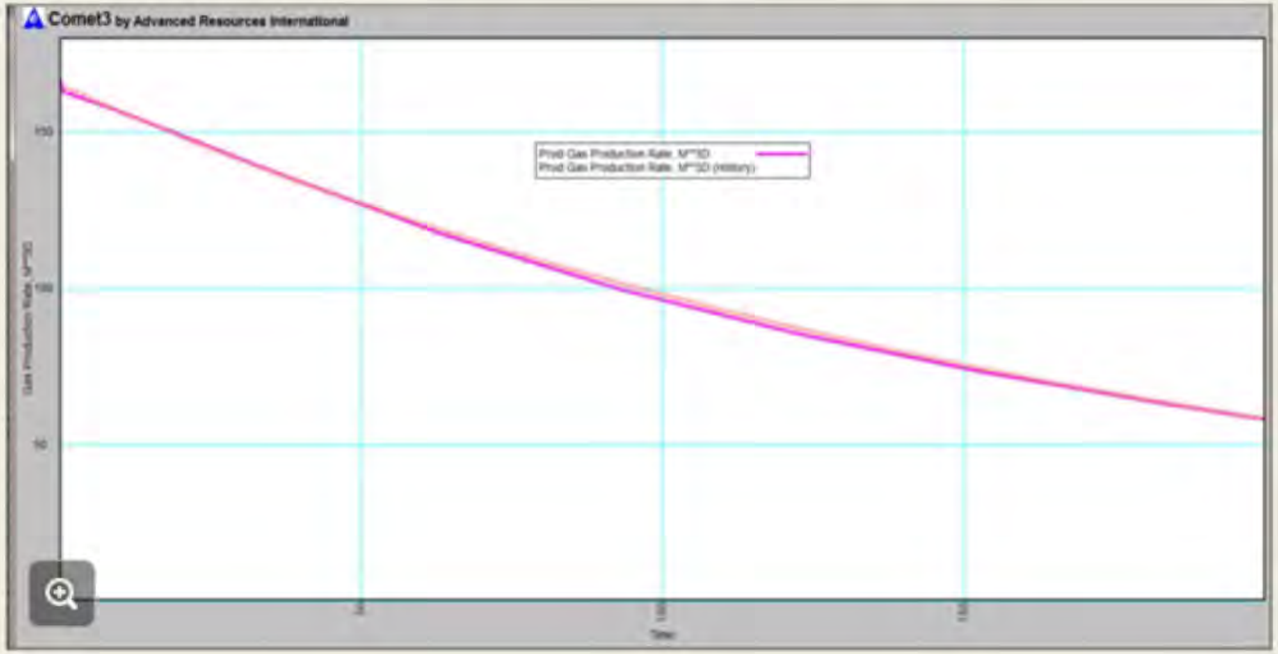
For improvement to gas drainage Alternative #2, each coal seam-wellhead vacuum pressure-pipe diameter combination was an option that the GMI team evaluated. Therefore, the GMI team evaluated 12 horizontal gob gas borehole options.

History Matching for Simulated Gas Prediction

If historic data inputs are available, reservoir simulation and engineering equations can be run using the data as inputs to compare simulation and calculated outputs to actual gas production. This "history matching" can further confirm the validity of the simulated and calculated gas prediction (see Module 4 for more information).

The analysis prepared for the Liulong mine pre-feasibility study report did not include history matching because there were insufficient historic data to input into the model for comparison of modeled results to actual gas production.

Example of a History Matching Chart



Quantifying the Benefits of Improvements & Gas Production Forecasting

Quantifying the Benefits of Improvements to Gas Drainage

The next step in a pre-feasibility study is normally assessing the benefits of improvements to gas drainage. The level of analysis depends on the extent and effectiveness of the existing gas drainage systems at the mine.

In the case of the Liulong Mine, existing gas drainage was very limited, and given the existing drainage practices, the mine could produce only 600,000 tpa of coal compared to the set target of 1.5 million tpa after acquisition. BMG recognized the need to completely replace the existing mine gas drainage approach. Therefore, a quantitative analysis of the improvements comparing existing gas drainage to the recommended alternatives would not provide great value to the study.

Instead, this portion of the study was merged with gas production forecasting (as discussed in Module 6) to focus on comparing proposed improvements under Alternatives #1 and #2.

Forecasting Gas Production: Evaluating Mine-wide Solutions

After evaluating the simulation results for the horizontal in-seam boreholes (Alternative #1, Options 1-4) and the calculated gas production rates for the horizontal gob boreholes (Alternative #2, Options 1-12), the GMI team developed mine-wide gas production forecasts, assessed risks, and prepared market and financial analyses for the three best solutions for improving gas drainage.

Improvement Alternative #1: In-seam pre-mine drainage boreholes		Improvement Alternative #2: Horizontal gob boreholes
Solution #1 (Alternative #1, Options 1 & 2)	**Solution #2 (Alternative #1, Options 3 & 4)**	**Solution #3 (Alternative #2, Options 5 & 11)**
In-seam pre-mine drainage boreholes penetrating mining seams at intervals of 30 m in Seam No. 3 and Seam No. 7.	In-seam pre-mine drainage boreholes penetrating mining seams at intervals of 10 m in Seam No. 3 and Seam No. 7.	Horizontal gob boreholes placed above mining seams (121 mm at 16 kPa) in Seam No. 3 and Seam No. 7.

With predicted gas production rates for in-seam boreholes and HGBs completed for individual longwall panels, the next step was to extrapolate those production rates across the entire mining operation.

Establishing a Mine Plan

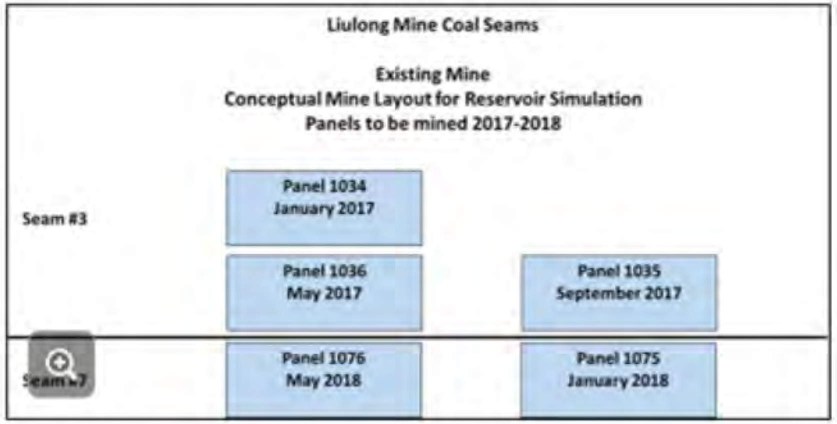
The first step to develop long-term gas production forecasts was to establish a mine plan based on:

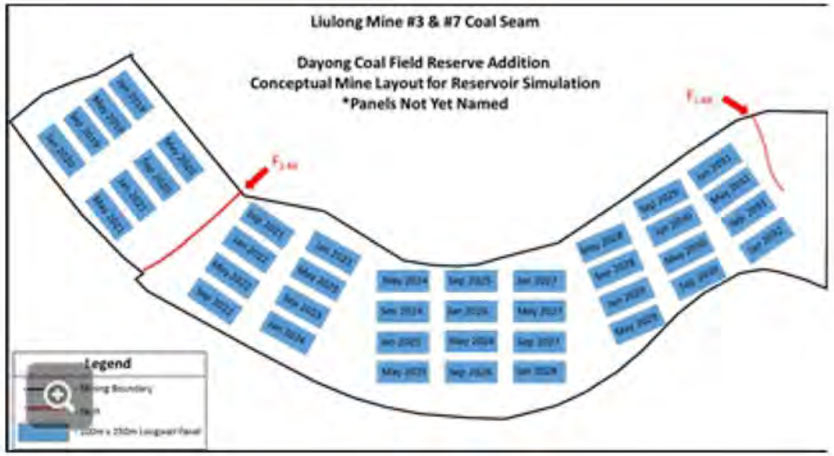
- The existing mine layout from BMG,
- The dimensions of the Dayong addition,
- Known advance rates, and
- Other factors.

Mine Production Plan and Conceptual Layout

The two diagrams on this slide present:

- The existing permitted mine production plan for the Liulong Mine with production from 2017 through 2018.
- The conceptual mine layout and future development and production plan for longwall panels (in uniform dimensions) from January 2019 through January 2032. The conceptual mine layout was developed specifically to forecast gas production and may change in the future.





The conceptual mine layout was used to forecast gas production for all three gas drainage solutions.

Mine Layout & Coal Production Plan: Solutions 1 and 2

With the conceptual mine layout and coal production plan established, the next steps were to establish borehole placement and timing to predict mine-wide gas production.

For in-seam pre-mine drainage boreholes (Solutions 1 and 2), the team:

- Established borehole locations using 30 m and 10 m borehole penetration spacing in Solutions 1 and 2.
- Assumed boreholes begin gas production upon completion, prior to longwall production.
- Assumed production from in-seam pre-drainage boreholes would terminate prior to the initiation of mining operations at each panel.

Mine Layout & Coal Production Plan: Solution 3

For the horizontal gob boreholes (Solution 3), the team assumed that:

- Three HGBs per panel would be drilled, and that drilling and completion would occur prior to commencement of longwall production at each panel.
- HGBs would be drilled the full length of the panel from the main.
- HGBs would not produce gas prior to longwall production.
- Production from HGBs would either extend six months after mining at each panel is completed or terminate once 100 percent of each seams’ gas resource was depleted, whichever occurred first.

Forecasting Gas Production

Once borehole spacing and drilling schedules were established, mine-wide gas production was forecasted using simulated production rates for in-seam boreholes and calculated production rates for HGBs.

Annual gas production was forecast from 2017 through 2032.

HGBs were forecast to deliver the highest gas production.

Forecasting Gas Production Results

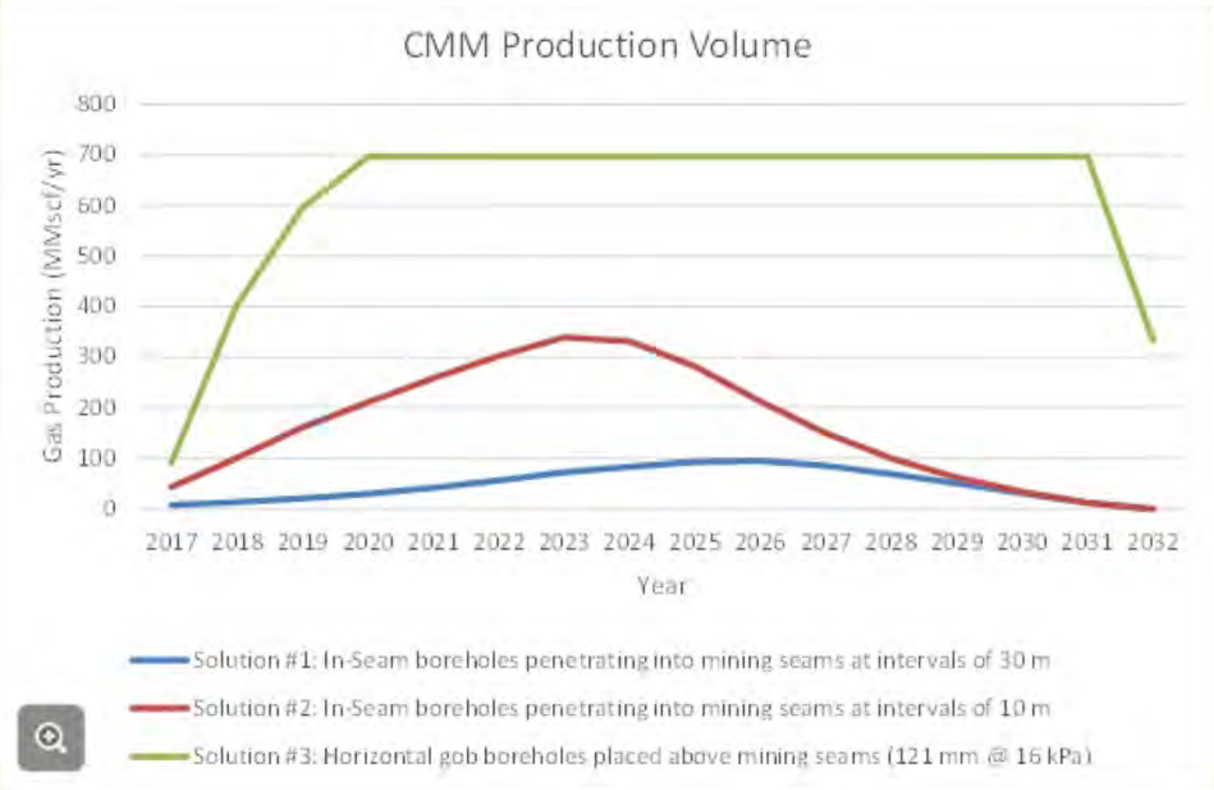
The GMI team forecasted gas production for all three gas drainage solutions for 15 years through 2032 based on the conceptual layout and the coal production plan.

As shown in the chart, Solution #3 (horizontal gob boreholes) was the most effective method to recover and produce CMM at the Liulong Mine.

Gob boreholes were not only more effective on an annual basis, but they were also more effective over the life of the project.

The three solutions were then evaluated to assess their market access, financial performance, and risk exposure.

Gas Production Forecast for Drainage Solutions



Market, Financial & Risk Analyses

Evaluation of CMM Markets

Having assessed CMM resources, evaluated gas drainage practice for improvements, and forecasted gas production, the GMI team then conducted an initial review of CMM markets.

The following slides show the market analysis conducted by the GMI team and BMG including:

- Identification of all potential markets
- Initial assessment of those markets
- Identification of markets with legitimate prospects
- Assessment of the remaining markets
- Preferred market including the basis for choosing that market

Initial Evaluation of CMM Markets at Liulong Mine

Seven potential markets were initially identified by the GMI Team and BMG; however, two were quickly eliminated based on available information leaving five potential markets for further analysis.

Market	Evaluation	Continue with Option?
Local natural gas distribution	A local distribution system is located in the area	Yes
Power generation: on-site use	Mines normally have large demand for electricity	Yes
Power generation: grid sales	A physical interconnect and sales to the grid are possible	Yes
Boiler fuel	There is typically demand at mines for hot water and steam	Yes
Natural gas transmission	There is no access to a high-pressure transmission line in the area	No
Industrial use	There are no industrial users within a reasonable distance to the surface gas production site	No
CNG/LNG	CNG could be possible; Gas quality is too low for LNG production	Yes

Second Evaluation of CMM Markets at Liulong Mine

The five remaining markets were further evaluated focusing on technical, logistical, economic, policy, and legal considerations. Based on this analysis, two options were identified as being realistic markets for a CMM project at the Liulong Mine.

Market	Evaluation	Continue with Option?
Local natural gas distribution	Subsidy available improving economics, but: system oversubscribed; capacity not available for many years; no existing interconnect from the mine's drainage system to the gas distribution system; low gas sales price – unlikely to be profitable	No
Power generation: on-site use	Demand for power at the mine: in line with corporate policy and has support of management; significant in-country experience with CMM power projects; capacity to design & build; could be economically attractive; offset high industrial electricity price; subsidy available	Yes
Power generation: grid sales	Subsidy available: physical grid interconnect possible; sales to the grid may be difficult	Yes
Boiler fuel	Limited demand for hot water/heating due to warm climate	No
Natural gas transmission	ELIMINATED IN FIRST EVALUATION	No
Industrial use	ELIMINATED IN FIRST EVALUATION	No
CNG/LNG	CNG and LNG are not economic	No

Final Evaluation of CMM Markets at Liulong Mine

In the final analysis, the GMI team and BMG determined that on-site power generation is the most viable market for a CMM project at the Liulong Mine due to the demand for power at the mine. It was also the preferred option by BMG, demonstrating management support for the project.

Market	Evaluation	Preferential Market for Project?
Local natural gas distribution	ELIMINATED IN SECOND EVALUATION	No
Power generation: on-site use	Preferred by mine company management; preliminary analysis indicates option is most economic	Yes
Power generation: grid sales	Economics are positive, but sales to the grid are difficult	No
Boiler fuel	ELIMINATED IN SECOND EVALUATION	No
Natural gas transmission	ELIMINATED IN FIRST EVALUATION	No
Industrial use	ELIMINATED IN FIRST EVALUATION	No
CNG/LNG	ELIMINATED IN SECOND EVALUATION	No

Risk Analysis

The GMI team considered project risks at a high level for this pre-feasibility study. However, the team did not include a discussion of project risks for the pre-feasibility study report due to the public nature of the report.

The following slides summarize the three types of risks evaluated:

- Technical
- Market
- Financial

Risks Evaluated: Technical

Risk	Impact	Mitigation
More rapid decline of gas supply than expected – isolation of sources, more rapid flooding, erroneous interpretation of data	Reduced revenue, early project termination, unable to deliver contracted energy supply	Improve forecasts: conduct in-depth investigations and testing in the full feasibility study and develop more detailed geological and decline reservoir models
Failure of a production well	No revenue until remedied	Install dual production pipes in entries (pre closure) or drill replacement borehole post closure
Loss of gas quality	Power or thermal energy supply reduced or in worst case, halted	Undertake remedial work on mine entry seals
Equipment failure	Loss of revenue until repaired	Detailed warranties; business interruption insurance; planned maintenance; use only OEM spares

Risks Evaluated: Market

Risk	Impact	Mitigation
Fall in power prices	Loss of revenue	Dual revenue streams; develop only high ROI projects so there is some flexibility
Carbon market collapses	Loss of carbon revenue	Dual revenue streams

Risks Evaluated: Financial

Risk	Impact	Mitigation
Carbon assets fail to deliver	Additional cost of emission reduction credits from the market	Business risk (once the contract is signed to deliver emission reductions)
Subsidies end	Project unable to deliver expected financial returns	Engage provincial and central governments to note impact

Financial Analysis Model Inputs

EPA built a simplified project-specific financial model in MS Excel®. The model design was based on more detailed financial models built for full CMM feasibility studies. The end use for the CMM project was on-site power to supply electricity to the mine.

The financial model calculated cash flows and produced financial metrics: Net Present Value (NPV), Internal Rate of Return (IRR), and Simple Payback Period.

Inputs for the model included:

- Gas production from gas production forecasts
- Power plant capacity calculated from available gas volumes
- Commodity pricing and subsidy pricing from the markets
- Values based on professional experience and expertise

Click the button to view the inputs that were used in the financial analysis. The inputs were based on information that the mine shared with the team, as well as from expert knowledge and experience of the team.

Financial Analysis Inputs

Physical & Financial Factors	Units	Value
Methane Concentration of Drained Gas	percent	98
Methane Concentration of Gob Gas	percent	70
Cost Escalation	percent	3.0
Price Escalation	percent	3.0
Capital Expenditures	Units	Value
Drainage System		
Borehole Cost	$/m	100 (in-seam); 130 (HGB)
Surface Vacuum Station	$/W	1.34
Vacuum Pump Efficiency	W/1000m^3/d	922
Gathering System		
Gathering Pipe Cost	$/m	75
Gathering Pipe Length	m/panel	450
Operating Expenses	Units	Value
Field Fuel Use (gas)	percent	10
O&M	$/1000m^3	17.66

Financial Analysis of Drainage Solutions

Based on the data provided and evaluation of the three drainage improvement solutions, the recommended gas drainage improvement solution was Solution #3 (HGBs). It yielded:

- ✓ The highest methane recovery and largest emission reduction potential
- ✓ The greatest power production potential
- ✓ The most cost-effective results

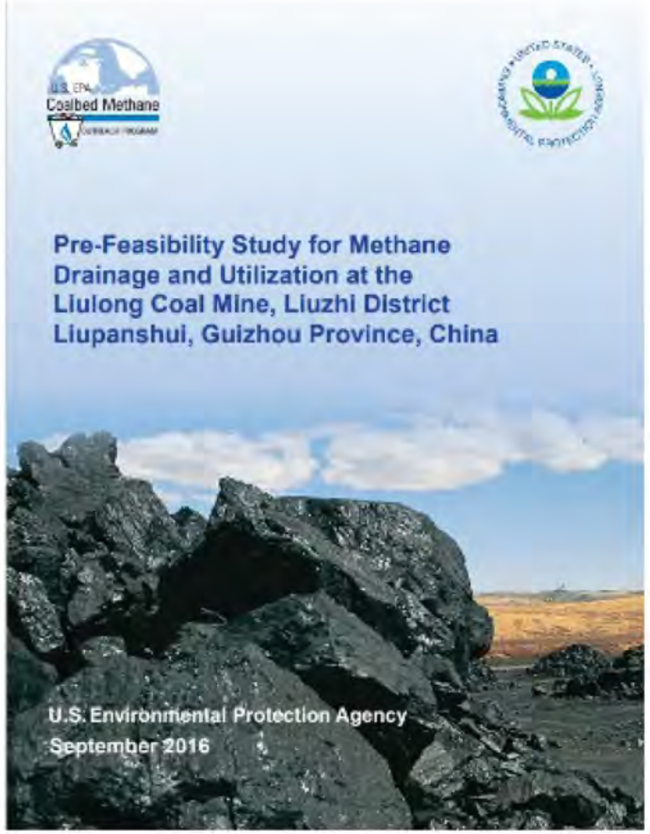
Solution	Description	Max Power Plant Capacity	NPV-10 US$000	IRR	Payback Year	Net CO_2e Reductions (Million metric tons) CO_2
1	In-seam boreholes penetrating mining seams at intervals of 30 m	2 MW	-5,722	-3%	-	0.32 Mt
2	In-seam boreholes penetrating mining seams at intervals of 10 m	6 MW	+1,278	+12%	8	1.1 Mt
3	Horizontal gob boreholes placed above mining seams	9 MW	+30,054	+43%	3	2.9 Mt

Recommended Next Steps

The following next steps were recommended in the pre-feasibility study report:

- ✓ Develop a clear mine layout for the Dayong coalfield with exact panel dimensions and coal production forecasts.
- ✓ Take additional core samples in the Dayong coalfield and conduct gas desorption analyses to obtain accurate measure of gas content, permeability, and porosity of the coals.
- ✓ Confirm the ability of the Liulong Mine to sell excess electricity to the power grid and confirm cost for a grid interconnect.
- ✓ Conduct pilot tests for both types of in-mine degasification technologies proposed in this study to develop more accurate production forecasts.
- ✓ Investigate and analyze more thoroughly all utilization options including power production to confirm the economic and technical feasibility of CMM-to-power and the viability of alternatives and their competitiveness with power generation.
- ✓ Begin investigation of financing options to confirm available sources of project finance so that BMG can determine the appropriate sources and mix of financing, including the mix of debt and equity.

Module 8 Summary



This module demonstrated how the steps in a pre-feasibility study (which were introduced in the previous modules of this training) were applied during the Liulong Mine case study.

Thank you!

You have completed Module 8.