

**UNECE**

# **Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Coal Mines**



**64**

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**Best Practice Guidance for Effective Methane Recovery and  
Use from Abandoned Coal Mines**

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## Foreword

Coal remains central to the energy mix of many countries. Inevitably, coal reserves are depleted as coal extraction progresses and mines are closed and abandoned. Abandoned mines continue to emit methane for many years after closure, yet their emissions remain unchecked and uncounted in many coal producing regions.

Methane is a powerful greenhouse gas (GHG), and recent research has shown that the impact of methane in the atmosphere is far more extensive than was originally thought. Coal mines are the fourth largest source of anthropogenic methane emissions after the oil and gas sectors, landfills and livestock industries. Technological advances have made it possible to significantly reduce methane emissions from the gassiest working mines. Closed mines can provide a small but significant opportunity to exploit a clean energy resource, known as Abandoned Mine Methane (AMM), that can be extracted and used. AMM capture and use offers many benefits, such as improved safety, air quality and health, energy supply and environmental performance. Technology exists that can recover methane from abandoned coal mines.

This document is aimed at raising awareness of AMM opportunities and hazards by providing accessible high-level guidance for senior corporate, government and financial decision-makers – all of whom play an integral role in decisions to implement best practices. Recommended principles and standards on coal mine methane (CMM) capture and use have already been set out in the Best Practice Guidance on Effective Methane Drainage and Use in Coal Mines. This document complements that guidance and is aimed at completing the coal mining cycle by considering the methane emissions that continue after mining has ceased and mines have closed.

The AMM Best Practice Guidance does not replace or supersede laws and regulations or other legally binding instruments, whether national or international. A clear legal framework and supportive policies can help in getting methane to market. The principles outlined herein are intended to provide guidance to complement existing legal and regulatory frameworks and to support development of post-mining projects to reduce the overall emissions attributable to the coal mining life cycle by optimising recovery and use of methane that would otherwise be released to the atmosphere. To gain a greater understanding about the potential growth of these emissions, UNECE member states and the Global Methane Initiative members are urged to consider ways to improve their knowledge of the magnitude and rate of growth of this emission source by including methane emissions from abandoned underground coal mines in their national inventories.

Guided by the Group of Experts on Coal Mine Methane, countries such as Poland and China have established International Centres of Excellence on CMM (ICE-CMM) to promote adoption of best practices in CMM extraction and use. The centres are positioned to disseminate AMM best practices in countries where they are established. In other countries, our hope is that similar agencies or organizations with responsibility for managing mine closures and AMM will find this guide practical and insightful in exploring options to utilize AMM resources.



**Olga Algayerova**  
Executive Secretary  
United Nations Economic  
Commission for Europe

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### Sponsoring Organisations

The **United Nations Economic Commission for Europe** (UNECE) is one of the five UN Regional Commissions that provides a forum through which 56 countries of North America and Western, Central, and Eastern Europe as well as Central Asia come together to forge the tools of their economic cooperation. The main areas of UNECE's activity are: economic cooperation and integration, environment policy, forests, housing and land, population, statistics, sustainable energy, trade, and transport. UNECE pursues its goals through policy analysis, the development of conventions, regulations and standards, and the provision of technical assistance. Energy related topics such as coal mining and coal mine methane are discussed by the member states in the Committee on Sustainable Energy (CSE). The Group of Experts on Coal Mine Methane convenes as a subsidiary body of the CSE meeting regularly to discuss issues and promote best practices for management, capture and use of the methane gas liberated during the coal mining life cycle ([www.unece.org/energy/se/cmm.html](http://www.unece.org/energy/se/cmm.html)).

The **Global Methane Initiative** (GMI) is an international public-private partnership that works with government agencies around the world to facilitate project development in five key methane-producing sectors: agricultural operations, coal mines, municipal solid waste, oil and gas systems, and wastewater. Launched in 2004, GMI works in concert with other international agreements, including the United Nations' Framework Convention on Climate Change (UNFCCC), to reduce greenhouse gas (GHG) emissions. Unlike other GHGs, methane is the primary component of natural gas and can be converted to usable energy. The reduction of methane emissions, therefore, serves as a cost-effective method to reduce GHGs and increase energy security, enhance economic growth, improve air quality and improve worker safety. The Global Methane Initiative is comprised of 44 partner countries and the European Commission, representing about 70 percent of the world's anthropogenic methane emissions. With respect to coal mine methane, GMI's Coal Subcommittee brings together key experts in coal mine methane recovery and utilisation to share information about state-of-the-art technologies and practices through a number of workshops, trainings, study tours, and capacity-building initiatives ([www.globalmethane.org](http://www.globalmethane.org)).

### Structure

The drafting work was assisted by the financial, technical and administrative support of the United States Environmental Protection Agency through GMI.

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## Acronyms

ACM	Approved Consolidated Methodology (UNFCCC)
AMM	Abandoned Mine Methane
CARB	California Air Resources Board
CDM	Clean Development Mechanism
CERs	Certified Emission Reductions
CH <sub>4</sub>	Methane
CHP	Combined Heat and Power
CMM	Coal Mine Methane
CNG	Compressed Natural Gas
CO <sub>2</sub>	Carbon Dioxide
CO <sub>2</sub> e	Carbon Dioxide Equivalent
EPA	United States Environmental Protection Agency
ETS	Emission Trading Scheme (European Union)
GHG	Greenhouse Gas
GIS	Geographic Information System
GMI	Global Methane Initiative
GWP	Global Warming Potential
kWh	Kilowatt-hour
m	Metre
m <sup>3</sup> /d	Cubic Metres per Day
m <sup>3</sup> /m	Cubic Metres per Minute
m <sup>3</sup> /t	Cubic Metres of Gas per Metric Tonne of Coal
Mt	Million Tonnes (metric)
Mtpa	Million Tonnes per Annum
MW <sub>e</sub>	Megawatt of Electricity Capacity
MWh	Megawatt-hour
NRDC	National Reform and Development Commission (People's Republic of China)
scfm	Standard Cubic Feet per Minute
SOCM	State-Owned Coal Mines

t	Tonne (metric) - equivalent to 1.102 short tons (US)
t/d	Tonnes per Day
TCVM	Town and Village Coal Mines
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
VERs	Verified Emission Reductions

## Glossary of Terms

Within the coal and mine gas industry, there is still confusion over terms and abbreviations used within and across different jurisdictions. In addition to the terms listed here, the UNECE has prepared a comprehensive Glossary of Coal Mine Methane Terms and Definitions that highlights how terminology is used in different regions.

To access the Glossary, please visit:

[http://www.unece.org/fileadmin/DAM/energy/se/pdfs/cmm/cmm4/ECE.ENERGY.GE.4.2008.3\\_e.pdf](http://www.unece.org/fileadmin/DAM/energy/se/pdfs/cmm/cmm4/ECE.ENERGY.GE.4.2008.3_e.pdf).

Abandoned mine methane (AMM) - the gas remaining, and in some instances newly generated by microbes, in abandoned coal mines held in voids, coal seams and other gas bearing strata that have been disturbed or intercepted by mining operations.

AMM resource - the total quantity of AMM remaining in the voids, coal seams and other gas bearing strata de-stressed by mining operations, plus any recently generated biogenic gas.

AMM reserves - the amount of the resource that it is recoverable making allowance for groundwater recovery at the maximum suction pressure that can be applied (50kPa to 70kPa for a tightly-sealed mine).

## Executive Summary

Closure of coal mines, and therefore Abandoned Mine Methane (AMM) emissions, will continue to be a relevant and important issue for the foreseeable future as countries continue to exploit and exhaust their coal reserves at a faster pace. This is true for many developed countries where coal production is declining, and mines are closing. However, this is also the case in some developed and developing economies where coal production will continue to play a significant role in the energy mix and closing mines are replaced by new mines. The total sum of emissions from closed and closing mines could, therefore, be substantial and will likely grow in importance. Forecasts of global coal mine methane emissions indicate that AMM represented 17% of the total mine methane emissions in 2010 and the proportion may increase to as much as 24% in 2050 (Kholod et al, 2018).

Cessation of coal mining due to exhaustion of commercially viable coal reserves does not halt gas emission. It is important to assess the magnitude of the AMM in place and potential emission rates due to uncontrolled surface emission risks, greenhouse gas emission concerns and utilisation opportunities. New methods of assessing emissions, from use of remote sensing to measuring methane concentrations in the atmosphere and pinpointing sources, to estimations based on historical coal production, may help countries more comprehensively identify and inventory methane resources. More precise estimates of the cumulative volume of emissions should focus attention on this potentially important source and may also drive supportive policy frameworks incentivizing investment.

Surface gas emission risks are a particular concern in mature coal mining areas which are heavily populated. The risk can be mitigated in many instances by passive venting. Where large quantities of AMM are identified, there may be opportunities for active gas extraction and utilisation of the gas as a clean energy resource. Active gas extraction will also help to minimise surface emission risks.

Once mining ceases, groundwater pumping, used to keep the active mine from flooding, is usually halted leading to flooding of the workings. This can also lead to progressive reduction in the accessible AMM resource and can potentially reduce connectivity from a gas production point to the gas reservoirs. The rate of flooding can vary according to the hydrogeology, extent, and depth of workings. In a few instances, groundwater pumping may be continued to protect deeper mine workings from flooding risks.

The potential environmental impacts, therefore, should be examined during mine closure, and suitable engineering measures designed and implemented to minimise risks to the environment. These measures together with a post closure monitoring strategy allow effective management of post mine closure emissions and risks.

The potential for extracting and exploiting AMM can be assessed at the same time as evaluating safety and environmental risks together with the need for appropriate control measures. The presence of methane in an abandoned mine is not sufficient reason alone for justifying development of an AMM extraction and utilisation scheme. A pre-feasibility study is needed as a first step.

Methods are available for estimating AMM resources and reserves. The methods used should be based on sound physical principles, use traceable data sources, recognise the uncertainties and potential risks and state all assumptions.

Uncertainties in the estimates are inevitable due to the difficulty of obtaining accurate data on water incursion in abandoned workings and the potential problems with air ingress as suction pressure is increased. Reserves should be discounted to take account of such uncertainty, and a reasoned explanation given for the discount factor applied.

Not all abandoned mines are suitable for AMM projects. Favourable mining and geological conditions must exist, but the most critical condition is a suitable end user to generate demand for the gas. Without a market for AMM-based energy, it is unlikely that there will be a viable and sustainable project. However, destruction of the gas by flaring may be feasible in some countries as a carbon offset project. Experience has shown that effort made at the pre-feasibility and feasibility stages of a project can significantly reduce both operational problems and future costs.

# 1. Introduction

## *Key messages*

- Mine closure is part of the natural resource development cycle in countries with declining coal production and in countries with sustained or growing coal production.
- Abandoned mine methane (AMM) emissions are an inevitable byproduct of the coal mining cycle and can persist for decades.
- Fugitive emissions of gas from abandoned mines can cause surface hazards if not properly managed and controlled.
- The AMM remaining in the unworked coal de-stressed by former longwall working can, in some instances, represent a major clean energy resource that can be exploited.
- Methane is a potent greenhouse gas (GHG) with a Global Warming Potential (GWP) that is 28-34 times that of carbon dioxide over a 100-year time frame, but with a significantly higher GWP of 84 over 10 years due to its 12-year atmospheric life.
- Recovery and use of AMM can also deliver important socio-economic benefits including technology development and job creation.
- The quantity of AMM available for release depends on various factors including the volume of un-worked coal in the strata disturbed by mining, the residual gas content of the coal still in place and the rate of flooding of the workings.
- Even if geologic and technological conditions are favourable, the lack of an enabling regulatory framework can render a project unattractive or even completely unworkable.

## *1.1 Objectives*

This guidance aims to assist mine operators, developers of gas resources, government regulators, oil & gas licensing authorities, redevelopment agencies and policymakers to take into account methane resources by identifying and increasing awareness of potential hazards associated with the continuing release of methane after mine closure and abandonment.

Important co-benefits of AMM extraction and use are significantly reducing the risk of uncontrolled emissions at the surface, exploiting an otherwise wasted gas resource and mitigating GHG emissions.

AMM extraction and use projects also help to meet the United Nations sustainable development goals of affordable and clean energy, and climate action.

## *1.2 Abandoned Mine Methane Overview*

AMM is the gas remaining after coal mine closure in gas-bearing strata that have been disturbed by mining, and in particular by longwall mining due to the large volumes of strata and coal disturbed. In some instances, additional methane can be generated by recent microbial activity. The fracturing of strata that occurs around coal mines and the nature of surficial deposits overlying bedrock often make sealing of abandoned shafts and drifts difficult and prone to leakage. As a result, fugitive emissions can arise, representing a public hazard, a GHG emission, and, potentially, a lost energy resource. For example, methane migrating into enclosed structures presents an explosive hazard, and methane released to the atmosphere

has a high global warming potential (GWP), 28-34 times that of CO<sub>2</sub> (IPCC, 2014) over 100 years, significantly contributing to climate change.<sup>1</sup> However, methane's GWP increases to 84 times that of CO<sub>2</sub> over the shorter horizon of 10 years due to its shorter atmospheric life of 12 years, amplifying the benefits of methane recovery and use to climate change mitigation. In addition to gas emission hazards and contributions to climate change, surface instability and mine water pollution problems can arise following the closure of a coal mine.

Climate change imperatives, other environmental objectives, and competition from renewables and natural gas are reducing reliance on coal as an energy source. Many of the major developed industrialised countries are experiencing a serious decline in coal production and are closing mines. However, even in countries, developed and developing, with active coal industries, mine closure is part of the natural resource development cycle. While extensive coal mine closure programmes can reduce coal availability, the potential for methane emissions could persist for decades (with the highest, most commercial volumes emitted in the first decade). Closure of mines, and therefore AMM emissions, will continue to be relevant and an important issue for the foreseeable future. The total sum of emissions from closed and closing mines could, therefore, be substantial and likely to grow in magnitude. Forecasts of global coal mine methane emissions indicate that AMM represented 17% of the total mine methane emissions in 2010, and the proportion may increase to as much as 24% in 2050 (Kholod et al, 2018).

Countries have made considerable efforts to encourage capture and use of gas at working coal mines but have placed less emphasis on reducing emissions and exploiting methane from abandoned mines. Aside from mitigation of climate change, recovery and use of AMM can deliver important societal benefits. Serious regional economic and social problems often arise as a result of extensive coal mine closures. Most developed countries have promulgated standards for mine closure and post-closure responsibility,<sup>2</sup> but in many developing economies, invariably little or no financial and regulatory provisions are made to identify responsible parties and manage post closure liabilities. Recovery and use of AMM can create new jobs, albeit a relatively small but nonetheless welcome contribution. Where AMM resources are sizeable there may be opportunities for developing industrial parks, the potentially low-cost, clean fuel providing an attractive benefit to commercial enterprises.

Geologic, technological, and market factors directly impact the success of an AMM project. In addition, the regulatory environment can be a critical factor when considering exploitation of AMM resources. Even if geologic and technological conditions are favourable, the lack of an enabling regulatory framework can render a project unattractive or even completely unworkable. Regulatory factors to consider are mine safety regulations, the licensing process, ownership rights, physical access, environmental regulations, taxation, post-closure liabilities

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<sup>1</sup> GWP of 28 is without climate carbon feedbacks and is the more commonly referenced GWP for methane. The GWP of 34 is with climate carbon feedbacks which measures the indirect effects of changes in carbon storage due to changes in climate. (see IPCC, 2014)

<sup>2</sup> United States Mine Safety and Health Administration, 30 Code of Federal Regulations 75.1204, New South Wales Work Health and Safety (Mines and Petroleum Sites) Regulations 2014, and Queensland Coal Mine Safety & Health Regulation 2017.



and fiscal regulations. Policymakers can play an important role in ensuring that these factors do not become barriers to commercializing AMM resources.

### *1.3 AMM Gas Extraction*

Technologies and management practices allow methane from abandoned mines to be extracted, providing significant environmental, economic, social and public safety benefits.

The methods for extracting gas from abandoned mines differ from those employed to capture and recover gas from working mines. Once a mine is sealed from the atmosphere, gas from all underground sources becomes potentially available for extraction at a single production location. Methane concentrations recovered from a well-sealed former gassy mine typically range from 15% to 90%, and with no oxygen. The other major gaseous components may be nitrogen, including de-oxygenated air, and carbon dioxide. Low concentrations of carbon monoxide and trace hydrocarbons such as ethane are sometimes present.

Access to abandoned mine workings for gas extraction is achieved through former shafts or drifts. When these are not suitable, for instance if they have been filled and no vent pipework has been installed, a gas extraction borehole can be drilled from the surface to intersect the underground workings. Initially there may be sufficient reservoir pressure to produce AMM at the surface. However, eventually suction, or vacuum, will be necessary to draw gas from the mine void, including former goaf/gob areas, from behind seals and the de-stressed in-situ coal. Gas compositions can vary in terms of methane concentration not only for each mine, but also as gas is extracted from different parts of a mine. The main factor affecting gas quality is dilution with air that is drawn into the mine from inadequately sealed surface entries. Uncontrolled air leakage will reduce the methane concentration of the gas and also limit the achievable suction and flow. Air ingress must be minimised to ensure stable gas quality and quantity. Air drawn into an abandoned mine could, conceivably in some instances, cause spontaneous combustion and the release of carbon monoxide.

The quantity of AMM available for release depends on various factors including the volume of un-worked coal in the strata disturbed by mining, the residual gas content of the coal still in place and the rate of flooding of the workings.

Individual small mine AMM projects are unlikely to be commercially viable unless aggregated. Integration of small and medium AMM projects with coal mine methane (CMM) schemes at working mines could increase flexibility and profitability by providing a source of gas to meet peak demands and a reservoir to store gas during low demand.

AMM extraction sites have been reported in Europe where extracted flows equal or even exceed CMM flows obtained from the working mine (Backhaus, 2018). In these instances, a significant volume of relatively recent biogenic methane may be present.

Flaring of AMM to mitigate emissions is currently not widely practised unless necessary for safety and/or environmental reasons. It can create a potential conflict with gas licensees in some countries and there are few incentives to flare AMM with the exception of the United States where AMM projects can participate in some carbon markets. Policy drivers will be discussed in more detail later in the document.

#### *1.4 AMM Emissions and Exploitation in Selected Countries*

Methane emissions avoided from the top AMM producing countries are shown in **Table 1.1**. It should be noted that emissions from many abandoned mines are often estimated rather than measured, with estimates based on accepted methodologies such as the Intergovernmental Panel on Climate Change methodology<sup>3</sup> or the methodology developed by the U.S. Environmental Protection Agency.<sup>4</sup> This contrasts with reported emissions from active mines which are often measured, either for purposes of tracking environmental performance or for health and safety monitoring. Generally, this leads to more uncertainty with reported AMM emissions.

China: Potential AMM resources have been identified in China (Coté, 2018b). At least 30,000 abandoned town and village coal mines (TCVMs) have been reported as abandoned, but most of these are likely to be too small to warrant AMM project development. In addition, 120 abandoned state-owned coal mines (SOCMs) have been identified. Of these, 50 have been reported as having potential for AMM production. In 2017, 150 million tonnes of coal production capacity were closed. However, a number of factors limit AMM potential in China, including often rapid flooding rates, intensive mining leading to removal of most of the gas sources in some areas, and an unclear regulatory environment in respect to ownership and responsibility for land, property and resources after mine closure. Liu (2018) described two AMM case studies and highlights future potential sites.

Germany: According to the GMI International Coal Mine Methane Projects Database, Germany has deployed more than 35 AMM projects and all of them involve electricity generation or combined heat and power (CHP) production. (GMI, 2017). As of 2015, there were 94 AMM-fired CHP units (one project usually involves several CHP units) with a combined installed generating capacity of 120 MWe.<sup>5</sup> These AMM projects generate more than 500 MWh of electricity and 75 MWh of heat annually, while avoiding 2.3 Mt of CO<sub>2</sub>e emissions (Backhaus, 2017). Most of Germany's AMM projects commenced in the early 2000s when an update in the country's renewable energy policy created a special feed-in-tariff for AMM and CMM-fired power generation. At the same time, annual reported GHG emissions from abandoned mines dropped from 5 Mt CO<sub>2</sub>e in 2000 to just 18,000 t CO<sub>2</sub>e in 2015 (UNFCCC, 2017). Active AMM projects utilized an estimated 99% of total methane emissions from abandoned mines in Germany in 2015 (Denysenko et al, 2019).

France: The last coal mine in France, La Houve, closed in 2004 but the capture and use of AMM in France began in 1978 in response to the Middle East Oil Crisis which began in 1973 and caused elevated oil prices to persist for several years. Since that time several gassy

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<sup>3</sup> IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy. Chapter 4, Fugitive Emissions. 2006. Geneva, Switzerland. [https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2\\_Volume2/V2\\_4\\_Ch4\\_Fugitive\\_Emissions.pdf](https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_4_Ch4_Fugitive_Emissions.pdf)

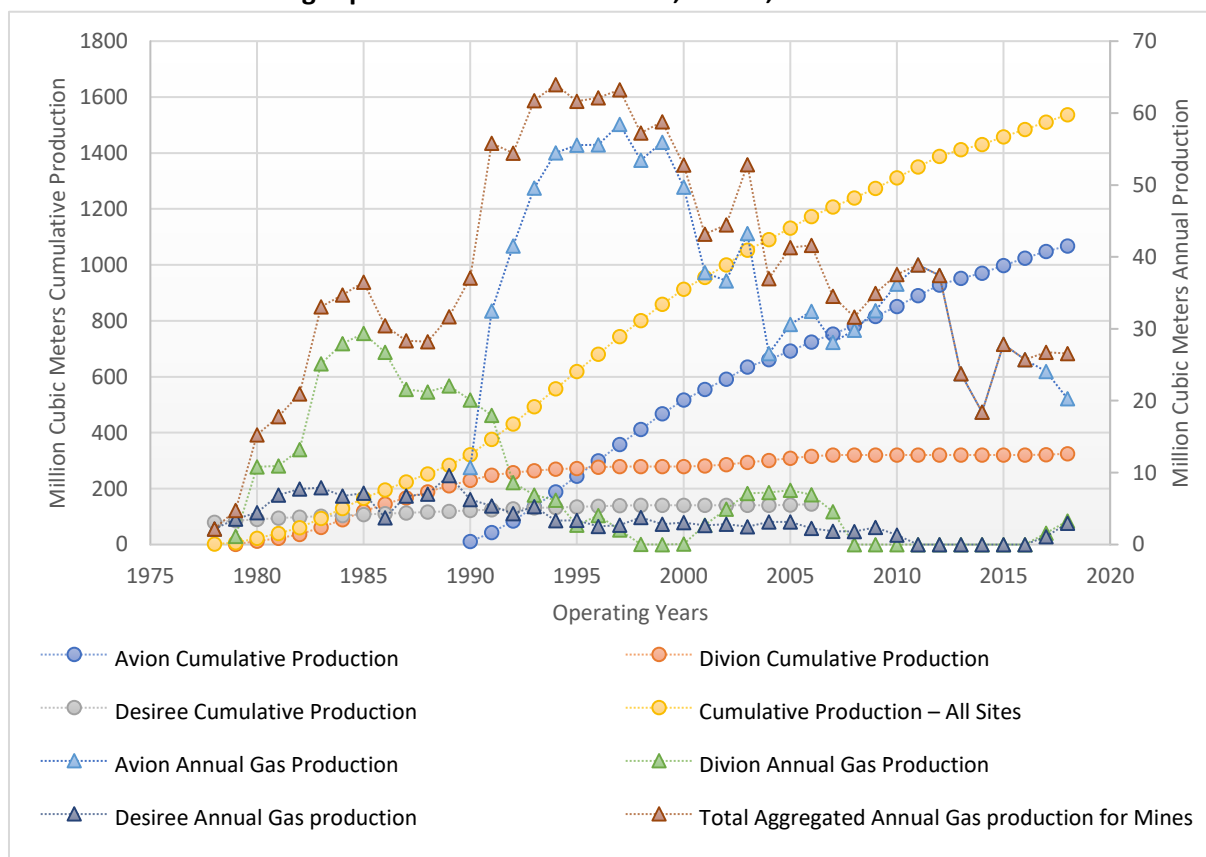
<sup>4</sup> EPA (2004). Methane Emissions from Abandoned Coal Mines In The United States: Emission Inventory Methodology and 1990-2002 Emissions Estimates. 2004. Washington, D.C. USA. [https://www.epa.gov/sites/production/files/2016-03/documents/amm\\_final\\_report.pdf](https://www.epa.gov/sites/production/files/2016-03/documents/amm_final_report.pdf)

<sup>5</sup> Backhaus, Clemens (2017). Experience with the utilization of coal mine gas from abandoned mine sin the region of North-Rhine-Westphalia, Germany. Workshop on Abandoned Mine Methane. UNECE Group of Experts on Coal Mine Methane. 23 October 2017. Geneva, Switzerland. [https://www.unece.org/fileadmin/DAM/energy/se/pdfs/cmm/cmm12/Workshop\\_2017/7.Mr.\\_Backhaus.pdf](https://www.unece.org/fileadmin/DAM/energy/se/pdfs/cmm/cmm12/Workshop_2017/7.Mr._Backhaus.pdf)

abandoned coal mines in northern France have produced gas which is injected into gas pipelines and used for electricity generation. For many years these activities were carried out by Gazenor, a former subsidiary of Charbonnages de France, the national coal company of France, which was disbanded in 2008. Three coal mining sites are the principal sources of gas production, Avion, Divion, and Desiree. **Figure 1.1** shows the annual and cumulative gas production from these abandoned mine sites (Moulin, 2019).

Francaise de l’Energie, a publicly traded company, purchased Gazenor in 2016 and presently controls approximately 1500 km<sup>2</sup> of concessions and operates the abandoned mine gas production sites and five electricity generation facilities with installed capacity of 9MW. From 1978 through 2018, Avion produced 1,068 million cubic meters of methane while Divion and Desiree each produced 325 and 145 million cubic meters of methane, respectively. Annual gas production in 2018 for the three mine sites was 26 million cubic meters of methane. Francaise de l’Energie estimates that over 600,000 tonnes of CO<sub>2</sub> emissions are avoided annually using the methane as a fuel to supplant coal.

**Figure 1.1**  
**Annual and cumulative gas production from the Avion, Divion, and Desiree Mines**



Source: Moulin, J., 2019

**United Kingdom:** By 1990, almost 80% of the underground coal mines in the United Kingdom had closed and by 2010, a high proportion of the AMM had been emitted or used (Fernando, 2011). AMM extraction was not considered viable from small mines, low-gas mines and mines closed for more than 10 years and flooded. By 2018, 150 coal mining areas had been closed and nearly 30 AMM power generation and gas supply projects developed, but not necessarily

synchronous in operation. As of October 2017, there were 13 AMM projects in operation. Twelve of these produce electricity (with a total installed capacity of 78 MWe) and one project involves pipeline injection (Kholod et al, 2018). Active AMM projects in the UK utilize about 58% of total methane emissions from abandoned mines. Abandoned mine methane emissions in the UK decreased from 1.4 Mt CO<sub>2</sub>e in 2000 to 0.441 Mt CO<sub>2</sub>e in 2015 (UNFCCC, 2017).

**United States:** In the United States, there are 7,500 abandoned mines, 524 of which are “gassy” (EPA, 2017; Global Methane Initiative, 2015). Historically AMM projects in the U.S. involved injection into existing natural gas pipelines; however, the number of AMM-based power and flaring projects has grown in recent years. There is a total of 19 AMM projects at 45 coal mines. These include aggregated projects including three AMM projects which group 3-5 mines into a single project, one AMM project which aggregates methane from 14 mines and three AMM projects combined with existing CMM projects (Coté, 2018a). Net abandoned mine methane emissions decreased from 8.8 Mt CO<sub>2</sub>e in 2000 to 6.4 Mt CO<sub>2</sub>e in 2017 due to increased use of AMM. Total AMM liberated increased to 9.2 Mt CO<sub>2</sub>e in 2017 with 2.7 Mt CO<sub>2</sub>e of that amount being used for power generation and pipeline gas sales (EPA, 2019). Coal production remains an important component of the energy mix in the U.S.; however, the number of underground mines declined to 237 in 2017 from 583 in 2008 due to competition from other fuels and the continued trend to higher production longwall mining.<sup>6</sup> The recent closure of many mines could present viable AMM opportunities.

Table 1.1

**Top AMM Producing Countries**

<i>Country</i>	<i>Number of projects</i>	<i>Emissions avoided (Mt CO<sub>2</sub>e)</i>	<i>Main AMM use</i>
China	Unknown	Believed to be small	Unknown
Czech Republic	10	0.36	Power generation
France	5	10.60	Industrial
Germany	40	5.71	Power generation
United Kingdom	20	0.64	Power generation
United States	20	2.70	Pipeline sales

*Source: EPA, 2015, CMM Country Profiles; EPA, 2017, U.S. GHG Inventory*

<sup>6</sup> U.S. Energy Information Administration. Annual Coal Report 2017 and Annual Coal Report 2008. November 2018 and March 2010 Washington, D.C. available at <https://www.eia.gov/coal/annual/>

## 2. Source of AMM Emissions

### Key messages

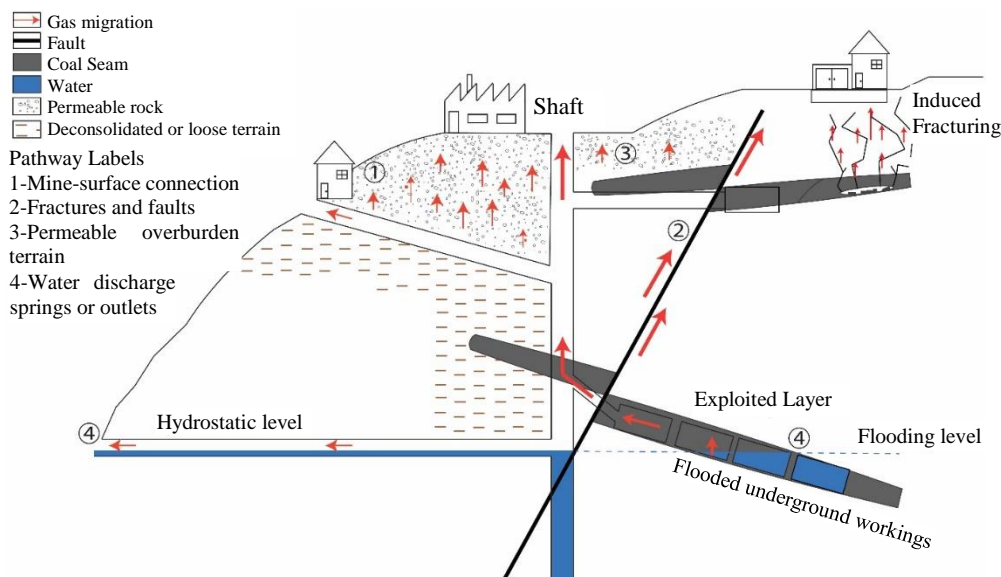
- When a coal mine is closed, the main mine ventilation fans stop, and there is a rapid and fundamental change in the composition and distribution of gases in the underground spaces.
- Methane and other hazardous gases will migrate to zones of lower pressure and may migrate to the surface if no impermeable strata or water bearing zones are encountered, potentially creating serious health and safety hazards.
- The mine may fill with water, impeding additional emissions although gases dissolved in water may be released when the water reaches the surface.
- Environmental and safety risks arising on, and near to, abandoned mine sites can be reduced by a range of actions, including installation of environmental monitoring systems, enhanced engineered sealing of mine entries, and active gas extraction.
- The implications of all these changes must be understood and the consequences managed.
- Environmental problems at closed mines can be managed, provided ownership of the residual coal, underground openings and the gas is clearly defined.

### 2.1 AMM Migration

When a mine closes, mechanical ventilation is immediately stopped, and gases are free to migrate through interconnected mine workings. Due to its buoyancy compared with air and other mine gases, methane will rise towards surface entries and shallow outcrop workings where underground connections exist. The most common pathways to the surface involve seepage through abandoned mine entries or from shallow workings through overlying fractured sandstone, particularly where there is only a thin cover of superficial deposits (**Figure 2.1**).

Figure 2.1

**Potential pathways for methane migration develop during after mining has ceased**



Source: Adapted from INERIS, 2019. Post-Mining Hazard Evaluation and Mapping in France

Such migration creates hazardous conditions in locations of closed mines for many decades, but also for any adjacent active mine. In addition, AMM migration can make it more difficult to evaluate AMM resources.

Potentially hazardous mine gases can, in some instances, enter buildings where they may accumulate to present a safety risk. Incidents have occurred in a number of former coal mining areas in Europe and Asia. In the UK, all the major coalfields have been affected at some time by surface emissions of mine gas. However, not all colliery closures necessarily lead to gas emission problems, as more than 900 deep mines were closed in the UK from 1947 to 1998 during which time only about 75 surface gas emission incidents were recorded. However, many more could have remained undetected. During the 1990s there was an average of about three new incidents per year, of which over 60% were attributed to leakages of gas through old, abandoned mine entries. While methane ignitions have occurred in residential buildings, there have been no fatalities. In contrast, blackdamp (carbon dioxide and nitrogen) emissions have led to a number of deaths.

In France, the French National Institute for Industrial Environment and Risks, INERIS, was commissioned to study hazards associated with abandoned mines and has published two handbooks. The latest provides information on post mining hazard evaluation and mapping to assist local authorities and planners (INERIS, 2019). The latter publication refers to a previous handbook (INERIS, 2016), which provides guidance on potentially hazardous gas emissions from closed and abandoned mines. The identified risks are ranked, ranging from the low risk of asphyxiation from toxic and/or flammable gases in the mine void which do not reach the lower explosion limit, to the high risk of asphyxiation or explosion where mine gases are emitted at a higher rate.

Interest in AMM in Germany began in the 1990's as mine closure began to increase. The initial concerns were specific to areas where leaking gas presented dangers to local inhabitants (Backhaus, 2017).

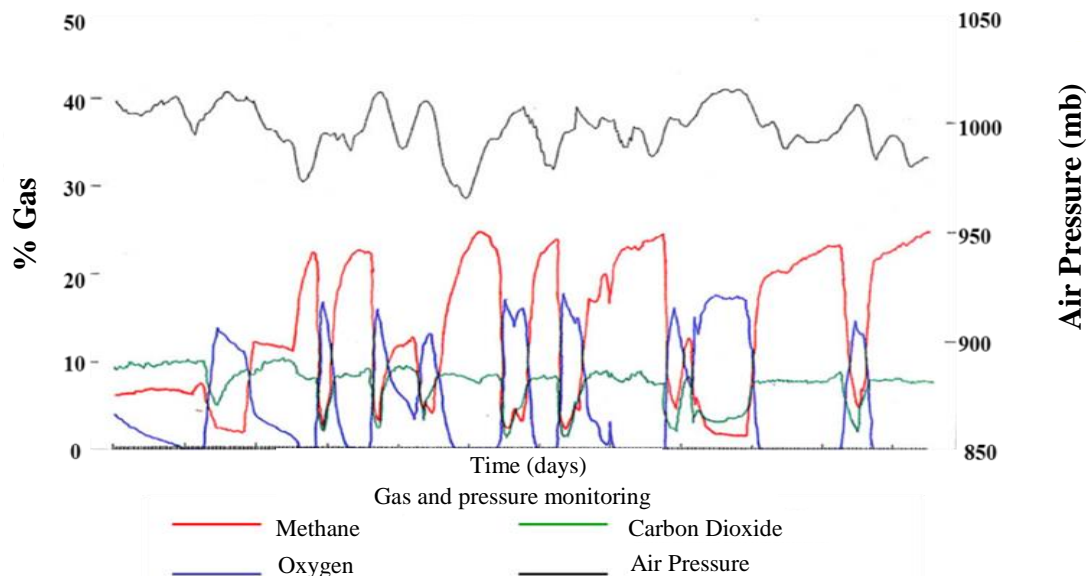
In Kazakhstan, many mines were developed and closed in rapid succession, particularly with the beginning of World War II. Such developments and closures were often carried out without thorough plans between the 1940s and 1970s. Migration of methane from old underground mine workings and mined voids subsequently led to increased gas hazards at the surface of currently and previously mined areas. In later decades, it was discovered that many building and settlements in mining regions of central Kazakhstan were built over former ventilation shafts and drifts. Sudden increases in methane concentrations, spontaneous combustion, surface instability, and deaths have occurred (Ostapov, 2006). In other cases, to avoid catastrophic events, the government had to relocate people, demolish buildings and close industrial facilities.

While there are no data from China, the largest coal mining country, on gas hazards at abandoned mine sites that have been overbuilt, it is likely that problems already exist but are not yet detected. Mine workings “breathe in and out” through any unsealed, or imperfectly sealed, surface connections in response to changes in atmospheric pressure as illustrated in **Figure 2.2** which shows the methane concentration increasing and decreasing periodically in response to ingress of air.

When atmospheric pressure is rising, air tends to flow into the abandoned mine workings producing air-rich mine gas mixtures. During periods of falling atmospheric pressure, the flow direction reverses bringing increasingly oxygen-deficient, methane-rich gas mixtures towards the surface. Mine gas problems are generally manifested at the surface during or immediately after a rapid fall in atmospheric pressure.

Figure 2.2

**Gas and pressure monitoring at a closed mine with imperfect sealing**



Source: Creedy, D. P., and K. Garner, 2002

Rising mine water will change the pressure of the mine void and can force gas out of the mine or into other permeable strata. The final water level will depend on the regional hydrologic setting. However, water pumping may be continued at closed mines to protect neighbouring, down-dip working mines from possible inrush and flooding should coal barriers separating the workings be breached. When evaluating an AMM resource, it is crucial to understand the interplay of these two factors. Multiple measurements should be taken over a period of time to account for breathing and overall changes in the void space pressure. The water level should be well-established and the rate of flooding should be known or estimated. A recently closed mine, for example, may appear to have a high gas production rate leading to estimates of a large gas resource, but the production rate could be the result of rapidly rising water levels compressing the gas and increasing the pressure. In the example shown in **Figure 2.3a**, the overall pressure of the mine void is decreasing through time, suggesting that the void is not filling with water, but the pressure in the mine depicted in **Figure 2.3b**, is increasing through time indicating that mine could be filling with water. Clearly, if water continues to fill the void space in the mine, the coal seams from which the gas is desorbing will become covered with water and the weight of the water column will eventually exert pressure that is greater than the desorption pressure and sufficient to stem the flow of gas from the seam.

Extensive mining of a coal basin can lead to workings of different ages and depths becoming interconnected. Such interconnections provide opportunities for gas to migrate over

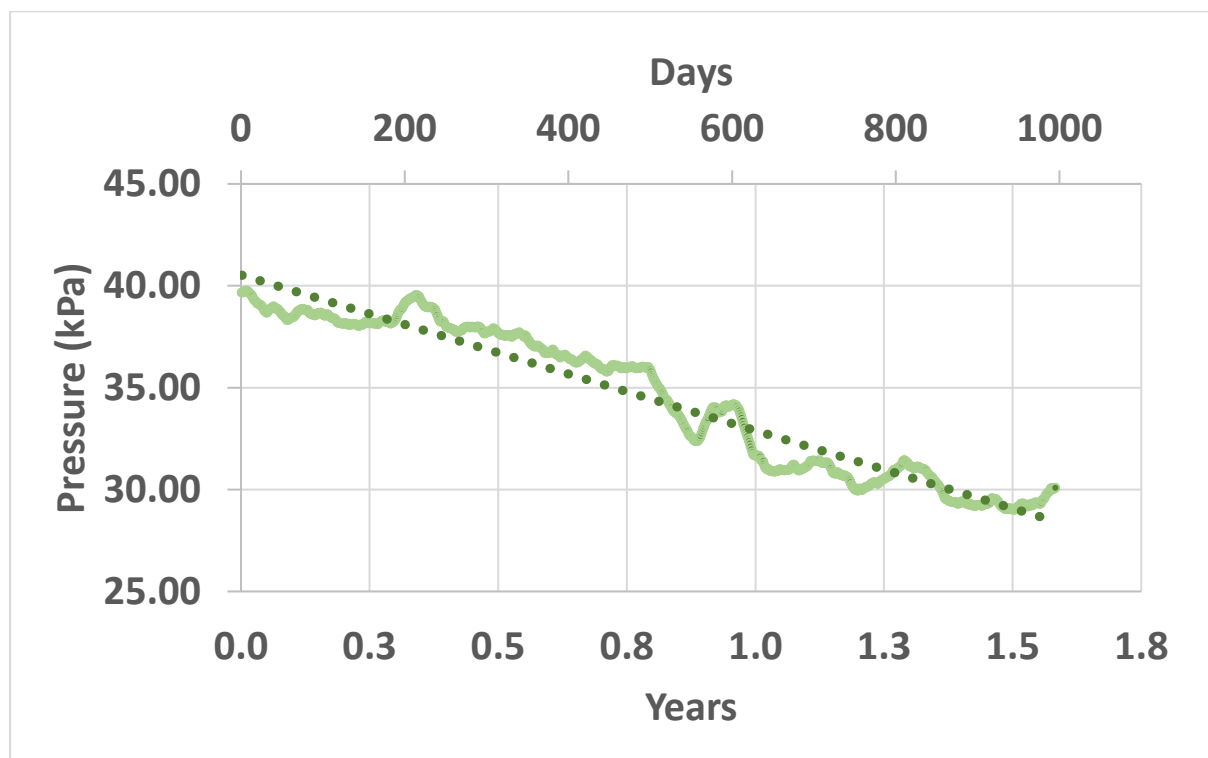
considerable distances following mine closure and, in some instances, can create surface gas emission problems beyond the curtilage of the mine just closed.

Uncontrolled gas emissions from closed coal mines generally fall into one of the following categories:

- A point source emission, detectable only over a few square metres of ground, usually traceable to a specific buried historic mine entry which has been inadequately sealed.
- A localised emission where gas has escaped from a specific mine entry and migrated along shallow, permeable migration pathways affecting a few tens of square metres of ground.
- An extended area emission where gas is migrating to the surface through surface cover overlying an extensive area of outcropping, permeable strata with shallow, gassy mine workings directly beneath.

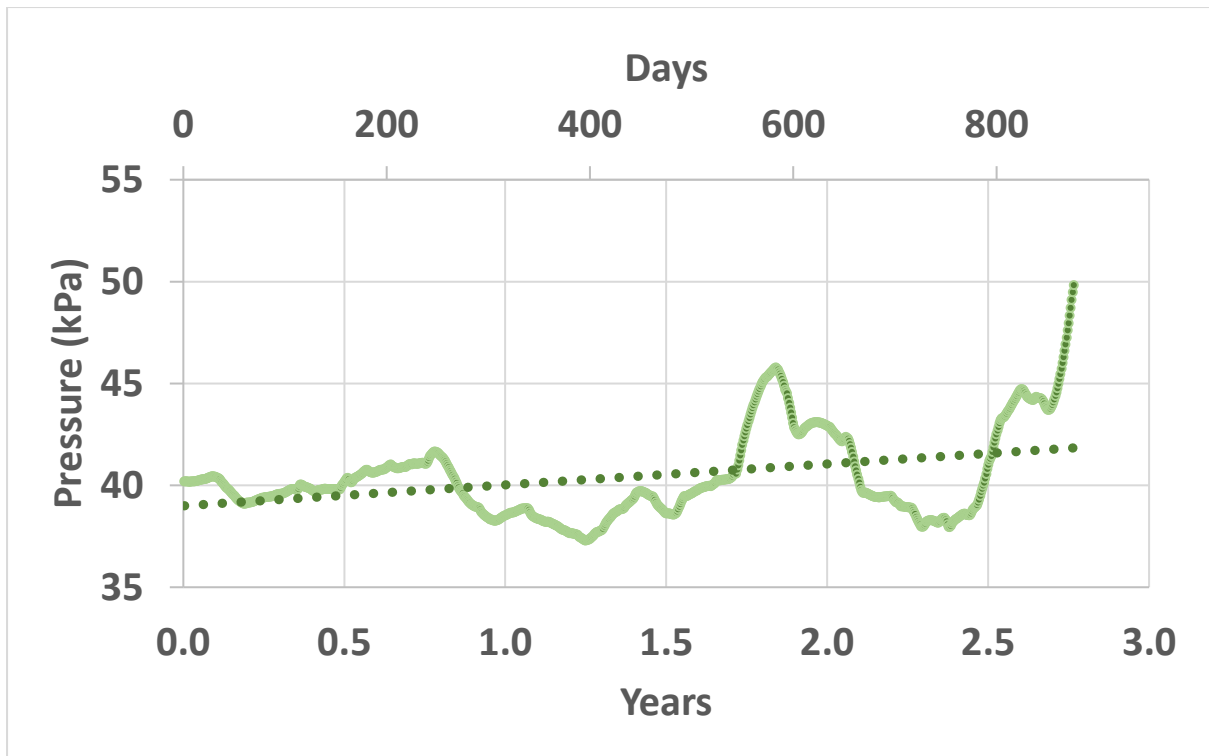
Figure 2.3

Gas pressure is plotted against time decreasing in (a) suggesting that water is not filling the mine void but increasing in (b) as water fills the void



(a)





(b)

Source: Pilcher, R., 2019, unpublished data modelling and analysis

The potential for such hazards to arise should be assessed as part of a coal mine closure procedure. Perfect sealing of former mine entries is difficult. As groundwater recovers in the abandoned workings, high gas pressures can arise and exacerbate fugitive emissions and escapes of gas into the ground. Installation of passive vents which allow for controlled release of gas can alleviate the risk (**Figure 2.4**). In more complex situations, where extended likely areas of emission have been identified, active extraction (gas pumping) can reduce the likelihood of surface gas hazards; the gas may not necessarily be of sufficient purity or available in sufficient quantity to warrant commercial utilisation.

Environmental and safety risks arising on, and near to, abandoned mine sites can be reduced by:

- Enhanced engineered sealing of mine entries (shafts, drifts and adits);
- Stabilisation of shallow workings and mine entries to prevent further ground movement;
- Installing gas pressure relief vents through mine entry seals;
- Use of active AMM extraction systems;
- Interception and treatment of mine-water discharges;
- Installation of environmental monitoring systems;
- Post closure inspection and monitoring;
- Incorporating structural gas barriers and sub-floor ventilation measures in industrial, commercial and residential buildings to prevent entry of hazardous gases.

Environmental problems at closed mines can be managed (**Box 1**) provided ownership of the residual coal, underground openings and the gas is clearly defined.

The UK Coal Authority is one example of a body formed by government to take on ownership of abandoned coal mine properties and which is empowered and funded to deal with historic liabilities that threaten the safety of the public. It also provides oversight on coal mine interaction, coal mine closure and AMM scheme closure, as the owner of the coal and former workings. It is also important to note that although managing closed mines can reduce safety hazards, this management does not reduce total emissions unless the methane is utilized.

## *2.2 Composition of gases in abandoned mines*

The gases most commonly encountered in abandoned coal mine workings are carbon dioxide, nitrogen, water vapour, oxygen and methane. The proportions of these gases can vary substantially from one coal field area to another and in some abandoned low-gas mines, only trace methane may be present. Ethane and other alkanes may also be detected in some former gassy mines. If the source of the extracted AMM are coal seams, the ratio of ethane to methane will increase as a result of differential desorption where longer chain alkane molecules desorb later than methane. AMM with an origin from non-coal reservoirs may have a markedly different composition. Carbon monoxide may be present as a result of low-temperature oxidation or incomplete combustion of carbonaceous material. Hydrogen sulphide and other trace gases can give a characteristic odour to mine gas emissions. The low concentrations of odorous gases normally do not pose a risk to health but may constitute an odour nuisance. The relative concentration of gas is important for environmental and safety reasons, but it also is key when planning the potential end-use for the gas.

### **Box 1. Example of a regulatory authority for addressing environmental hazards associated with closed coal mines**

The UK Coal Authority - a government organisation responsible for managing historic liabilities associated with abandoned mines that have reverted into its ownership. A programme of inspection and monitoring of its abandoned coal mine sites has been implemented to enable potential problems to be detected and forestalled. Emergency response arrangements ensure any incident is rapidly attended and treated once reported. The monitoring programme includes:

- Measuring gas composition, flow and pressure at mine vents installed to ensure controlled emission;
- Inspection of flame traps and vents to ensure they are not blocked;
- Measuring water levels in shafts and monitoring boreholes, discharge flows and water quality;
- Maintaining the security of monitoring, venting and water treatment sites;
- Audit and review of the results.

Table 2.1

**Composition samples from abandoned mines in Illinois coal basin, USA**

County in State of Illinois	Mine or Borehole	Depth (ft)	Gas Composition						Heating Value MJ/m <sup>3</sup>
			CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>3</sub> H <sub>8</sub>	
Christian	Joe Simkins #1		16.3	1.1	63.1	19.0	0.5	0.2	7.5
Clinton	Breese-Trenton	435	11.8	0.4	27.1	60.3	0.2	0.1	23.1
Clinton	Pessina #1		10.2	0.3	20.7	68.8	ND	ND	25.9
Franklin	Zeigler	380	5.9	0.6	28.8	64.7	ND	ND	24.4
Franklin	Peabody #1	535	8.2	0.7	13.8	77.3	0.2	ND	29.2
Gallatin	B & W Coal		0.1	20.7	79.2	ND	ND	ND	-
Montgomery	G. Stieren, Crown #1	362	5.5	ND	24.4	69.8	0.2	ND	26.5
Perry	F. Hepp, Bernard Mine	105	19.0	0.8	56.8	23.4	ND	ND	8.8
Randolph	Moffat Coal #2		3.3	11.6	85.1	ND	ND	ND	-
St. Clair	Peabody Coal, test hole	126	0.3	ND	10.5	89.2	ND	ND	33.6
Saline	Charter Oil #1A		ND	0.6	12.8	75.9	9.5	ND	35.8
Saline	A. Farris, Dering Mine	460	4.0	0.5	5.2	90.3	ND	ND	34.1
Saline	A. Farris, Dering Mine		5.5	0.1	3.4	90.9	ND	ND	34.3
Saline	Wasson Mine shaft		6.2	0.6	40.7	51.0	1.5	ND	20.2
Saline	M.L. Devillez #3		3.3	4.1	50.8	41.8	ND	ND	15.8
Saline	W. Duncan, Cook-Spear #1	439	5.7	0.3	7.3	85.7	ND	ND	32.4
Saline	Adams Unit #1 (Sahara #10)		6.2	0.2	2.2	90.2	ND	ND	34.2
Saline	Jade Oil, Dering Mine		6.2	1.5	8.9	83.4	ND	ND	31.4
Saline	Sahara #10 Mine	445	8.7	3.5	64.8	23.0	ND	ND	8.7
Saline	Dan January		3.1	0.7	9.8	86.3	ND	ND	32.6
Saline	J. Wilson, Sahara (O'Gara #8)	405	6.1	0.2	3.1	90.6	ND	ND	34.2
Saline	Frank Genet Mine		8.6	0.8	ND	90.1	ND	ND	34.0
Saline	Sahara #1 Mine		7.0	3.7	72.7	16.6	ND	ND	6.3
Vermilion	Bunsenville Mine		6.5	14.4	79.1	ND	ND	ND	-

Source: Demir, I., et al, 2004

Note: ND = not detected

**Table 2.1** illustrates the variability in gas composition that was found in abandoned coal mines located in the Illinois coal basin. The range in gas composition is controlled by many factors, most important of which is the degree to which the mine is sealed to prevent air ingress. High oxygen and nitrogen content indicate a high proportion of air ingress, whereas the mines that exhibit high hydrocarbon concentrations indicate that mine's openings are relatively well sealed and are not allowing air to flow into the mine during periods of high atmospheric pressure. Mines may be compartmentalized due to layout of the workings or post closure subsidence and roof collapse, causing composition to vary within the mine if there is no direct communication that allows flow of gases from one area to another.

Figure 2.4

**Gas vents on an abandoned mine shaft, UK**



Source: Creedy, D. P., and K. Garner, 2002

### 3. Quantifying AMM Resources and Predicting Gas Flow Rates

#### Key messages

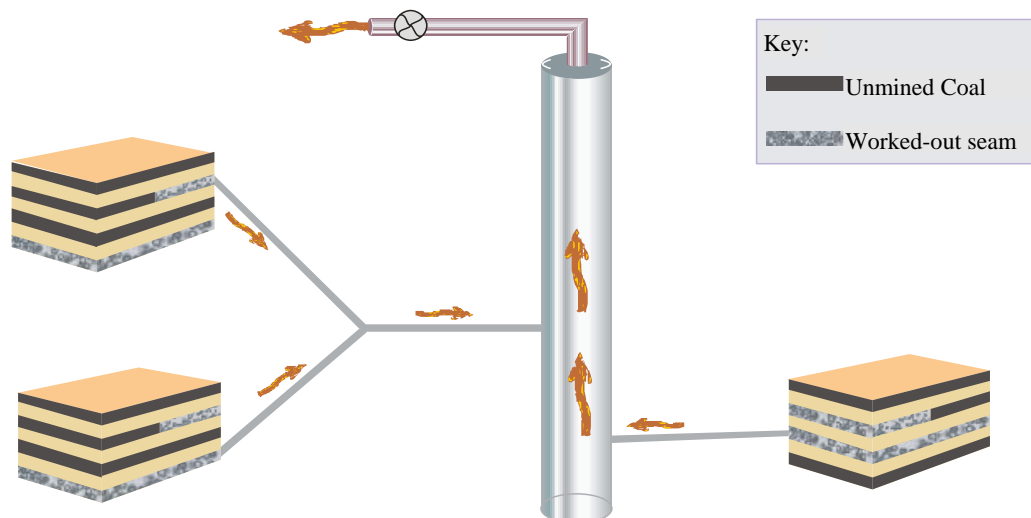
- Characterisation of the AMM reservoir is an essential first stage of the work in order to estimate the potentially recoverable gas reserves after taking account of the effects of mine-water recovery, flooding of connecting roadways and engineering works that may be needed to control air ingress.
- An AMM reservoir comprises the coal seams and any additional gas-bearing rocks within strata de-stressed by former longwall coal extraction. In some instances, it may also include methane of biogenic origin.
- Abandoned mine roadways provide conduits to direct AMM to a selected production well, shaft or drift.
- The de-stressing effects of non-caving mining methods, such as room and pillar, are significantly smaller than those of longwall and are often excluded from gas resource calculations.
- The potential production gas flow rate can be estimated by using measured gas emission data from the mine before closure to extrapolate exponential or hyperbolic decay curves.
- Actual flow rates can be determined by production testing using an extraction pump.
- The effectiveness of gas extraction could be compromised where there are fresh air leakages into the mine workings through imperfectly sealed surface entries.

#### 3.1 AMM Resource

The amount of coal-seam derived AMM depends on the area thickness and residual gas content of coal seams remaining after mining and within the zone of influence of the former mining. Geology-based estimates of AMM resources can be made using a simple model which combines information from mine plans, geological logs, water inflow data and in situ gas content measurements. A conceptual AMM reservoir is illustrated in **Figure 3.1**.

Figure 3.1

#### AMM reservoir concept model



Research undertaken in Europe suggests that a longwall AMM reservoir will typically include coal seams up to 160m – 200m above, in the roof, and 40m – 70m below, in the floor (UNECE, 2016). Where strong strata are present, particularly in the roof, the de-stressing height may be considerably reduced. Only a proportion of the virgin seam gas content of roof and floor seams is emitted during working, the magnitude depending on the proximity of the disturbed unworked coal seam to the worked seam and permeability to gas. Where a number of seams, each one stacked above the other, have been worked in succession, the cumulative degassing effect of each working must be considered in determining the residual gas resource.

### *3.2 AMM Reserves*

The AMM reserves are the volumes of gas that can be extracted, having taken flooding rate into account. Flooding will progressively isolate AMM sources as water rises in the old workings. It will not only reduce the volume of the accessible gas reservoir, but may also isolate parts of the workings by flooding connecting roadways. Localised flooding can limit the ability of the surface extraction pumps to exert a negative suction pressure throughout the abandoned workings. Mine water pumping records prior to closure provide an indication of likely water inflow, but the sealing of mine entries and removal of surface water connections may attenuate this value.

Whilst it is technically possible to de-water a mine to maximise AMM extraction, this is generally unlikely to be financially viable. Discharge of groundwater at the surface may also come under restrictive environmental guidelines, potentially adding complexity and cost. The level of water in an abandoned mine is therefore an important constraint on AMM prospects. There is often a limited ‘window of opportunity’ to exploit AMM from mines before they become flooded.

Underground roadways provide the means of transmitting suction pressure from surface pumps to the primary gas reservoirs. Suction is needed to generate pressure gradients and maintain desorption of gas from the coal. The less suction applied, the less gas will be recovered. The gas production process, therefore, largely relies on gas desorbing from primary coal seam sources entering goaf areas and gas extraction pumps drawing leakage gas through multiple stoppings; only small leakages from a large number of stoppings may be needed to maintain a production flow. At the low flow rates required, pressure losses across stoppings are insignificant. In some instances, the effectiveness of gas extraction could be compromised where there are fresh air leakages into the mine workings through imperfectly sealed surface entries.

In mines that have been abandoned for some years prior to installation of a gas extraction system, mine-water may have accumulated in some goaf areas and displaced methane into roadways and shallower seam workings. The displaced gas may be accessible for production and, if pressurised may initially enable high flow rates to be obtained. However, the total volume of available gas may be too small to support a commercial AMM scheme.

Once a goaf area has been flooded, the associated primary gas sources can no longer release gas into the workings. The resource is not lost but de-watering will be required before desorption processes can be re-established.

Overall, the recoverable volume of AMM depends on:

- Remaining gas content of the mined seam and any gas-bearing rock or coal strata within the zone of influence;
- The void volume of old workings and the rate of flooding;
- Interconnectivity of the former coal production areas and goafs;
- Desorption characteristics of the coal, and gas pressure;
- Quality of surface seals.

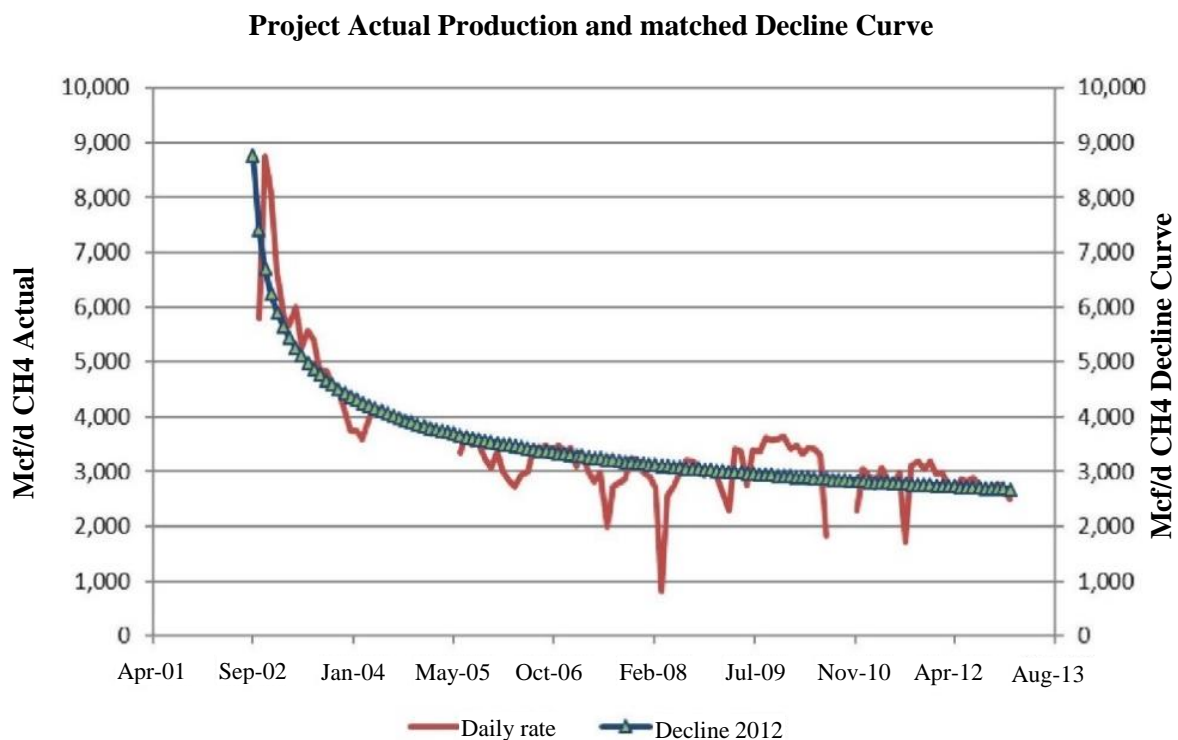
### 3.3 Predicting AMM Flow Rate

The potential production gas flow rate can be estimated by using measured gas emission data from the mine before closure to extrapolate exponential or hyperbolic decay curves. Actual flow rates can be determined by production testing using an extraction pump. It is important to understand that rapid flooding can lead to rapid reductions in flow rate and significantly reduced recovery. High gas pressure in abandoned mine workings can be an indicator of pressurisation due to water level rise in a well-sealed system.

Extrapolated hyperbolic decline curves, based on measured data, are frequently used to estimate AMM emissions from abandoned mines (**Figure 3.2**). The total area under a decline curve represents the recoverable AMM, provided no new perturbing factors come into play. However, extrapolation of AMM emissions from only a few data points is inherently unreliable as it does not take account of different void volumes in different mined seams, and hence, variability in water recovery.

Figure 3.2

#### An AMM emission decline curve

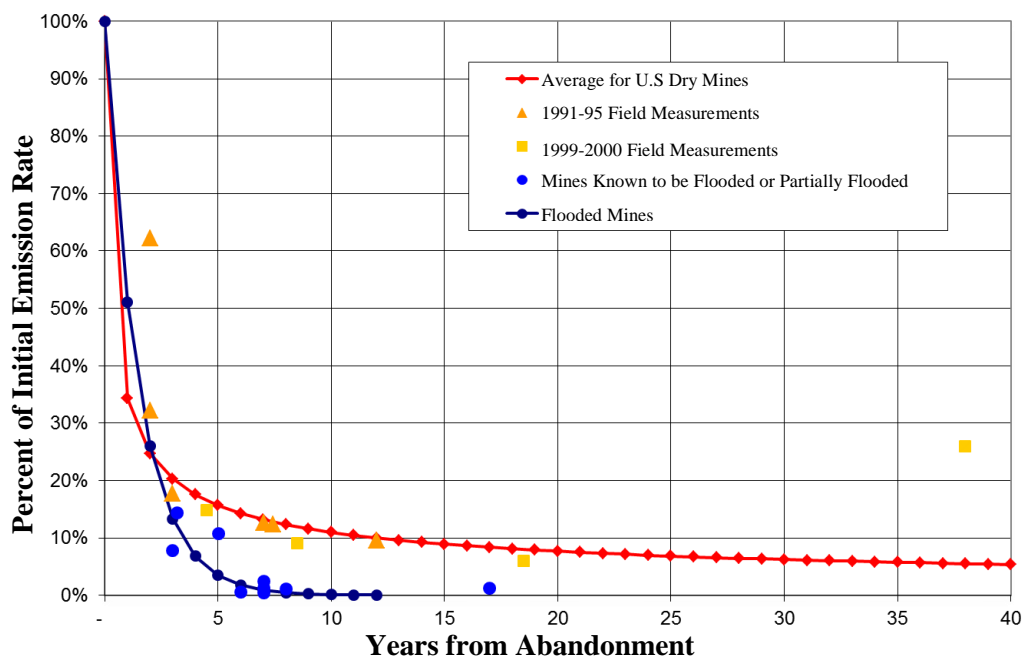


Source: Coté, M., 2018c

A robust process for determining likely AMM availability for exploitation will include calculations of AMM-in-place using geological, mining and residual gas content data. The reservoir boundaries are defined by the extent of former longwall de-stressing zones and the gas resource is the gas remaining in unworked coal that has been disturbed by former longwall extraction.

Recoverable gas will depend on interconnectivity of mine workings, standards of entry sealing and flooding rates. The latter can be estimated on a seam by seam basis using a measured or estimated water inflow rate and void estimates at each mining level. Thus, the AMM reserves are a function of flooding depth (**Figure 3.3**).

Figure 3.3  
**Plot showing the difference in the rate of decline in potential emissions for dry versus flooded mines**



Source: Coté, M., et al, 2003

Mean desorbable remaining gas content in the UK, for example, typically varies from 25% to 50% of the original virgin gas content for the reference coal seam. In AMM reservoirs where the overlying seams have been extensively mined, a value of 25% is used for first order estimates; where workings are limited to a single extracted seam and there are a number of coals in the de-stressed envelope a value of 50% is used. In most instances the figure will be between the two and a default value of 35% is considered appropriate.

Remaining desorbable gas content can also be estimated using empirical relationships (Creedy & Kershaw, 1988) derived from gas content measurements from boreholes drilled through old workings (Creedy, 1985).

By combining water level as a function of time with the gas reserve as a function of depth, it is possible to obtain a function of AMM reserve against time (Kershaw, 2005).



## 4. Evaluating Feasibility of AMM Extraction and Use

### *Key messages*

- Commercial success of an AMM scheme will depend on its ability to compete with other fuels and sources of energy in the market place.
- Appraisal of feasibility of AMM projects involves consideration of mining, geological, surface and planning issues together with gas and electricity markets and policy environment.
- Various utilisation options are available for AMM schemes and are dependent on a range of factors including energy prices, access to the gas, incentives and other factors.
- Development and implementation of an AMM project should include a well-defined gas production strategy and recognition that production will likely be from a decaying resource.

### *4.1 Factors in Assessing Feasibility of AMM Projects*

An appraisal of feasibility of AMM projects involves consideration of mining, geological, surface and planning issues together with gas and electricity markets and policy environment. Schemes must not only address the technical challenges of gas extraction, for example, controlling air ingress and water recovery, but also the requirements of the end user.

The level of detail in a study and the reliability of the results will depend on the closure status of the mine and availability of records. Typical situations are:

1. Mine abandoned some time ago, few or no records remain, limited empirical data available;
2. Mine abandoned recently with good historical data available but some gaps;
3. Mine closure is in progress and all relevant data is accessible.

The commercial success of an AMM scheme will depend on its ability to compete with other fuels and sources of energy in the marketplace. The use of AMM will be influenced by:

- Availability, quantity and quality of the gas;
- Customer requirements and contract conditions;
- Cost and availability of alternative fuels;
- Regulatory and legal framework;
- Any incentives, which governments often create because of the social benefits of AMM utilization;
- Capital and operating costs;
- Site access.

Not all abandoned mines will be suitable for AMM exploitation. Some closed mines which worked coal seams with low gas-contents produce mixtures of de-oxygenated air and carbon dioxide (blackdamp). There are exceptions, however. A low gas mine has been reported as becoming an AMM producer, possibly as a result of microbial methane generation (Backhaus, 2018).

Where coal extraction has been extensive, or where there are few coal seams in the strata above and below worked coal seams, the AMM potential may be low. Other factors will also influence the suitability of an abandoned mine for an AMM project (**Box 2**); in general, these are linked to the ability to control air ingress and the rate of water recovery within the abandoned workings.

#### 4.2 Gas Production Strategies

There are various options to be considered in determining a gas production strategy to maximise revenue and customer benefits:

- Extract as much gas as possible prior to closure using conventional gas drainage techniques while the primary gas extraction sites are accessible, and the process is controllable.
- Maximise extraction after closure and early sealing, while gas flows are highest, to recover the maximum volume of gas before flooding eliminates the degassing sources.
- Produce AMM to match a specific user demand.

Consideration should also be given to optimising use of the decaying AMM source:

- Produce and use AMM at less than the maximum extraction rate but risk reduced producible gas reserves due to continuing groundwater recovery.
- Only produce AMM to satisfy peak demand to benefit from high peak tariffs for power generation.
- Co-generation with natural gas where the production cost of AMM is less than the purchase price of natural gas.
- Use of portable packaged generating systems so excess capacity can be relocated, but alternative sites must be available and ready to receive surplus equipment.

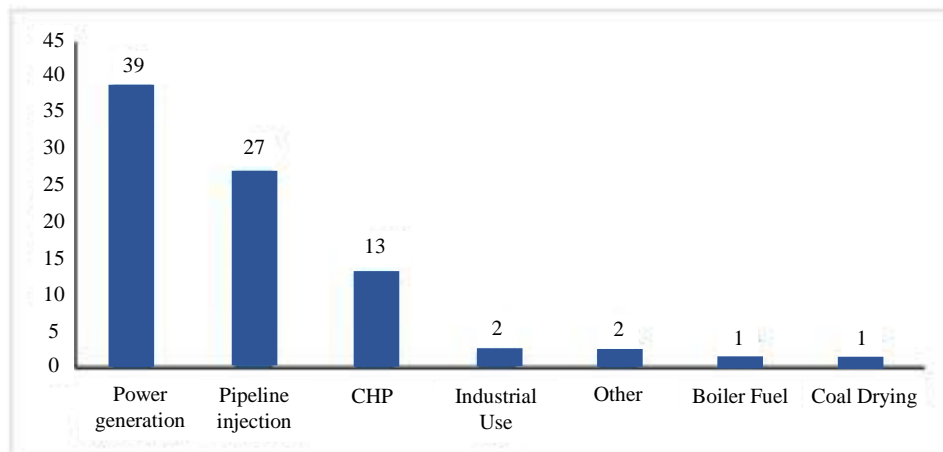
#### **Box 2. Key features of a promising AMM project mine**

- An extensive area of interconnected abandoned workings;
- A large coal volume in unmined seams de-stressed by under- and overworking (i.e. a significant thickness of coal seams above and below the worked coal seams);
- Use of longwall total caving methods of extraction;
- Significant residual methane in the unmined coal seams;
- Minimal water ingress;
- The ability to reduce water ingress as part of the closure programme;
- A mine layout which encourages flow of water to lowest workings with little or no ponding in main roadways;
- Minimum number of mine entries;
- An unfilled shaft or drift from which gas can be extracted or a suitable site for drilling a gas extraction borehole;
- Good records of historic treatment of mine shafts;
- No connections to shallow outcrop workings so no air in-leakage;
- Surface access for infrastructure and development;
- Local market for gas or small-scale power generation and high energy prices.

### 4.3 AMM Utilisation Options

Various utilisation options are available for AMM schemes and are similar to those available for natural gas use. Energy prices, gas and electricity transmission arrangements, regulation and incentives, infrastructure and access, planning, environmental issues, corporate objectives, and customer requirements need to be considered in selecting the most appropriate end use option.

Figure 4.1  
**Global AMM projects**



Source: Global Methane Initiative, 2016

Depending on gas quality and other factors, options for commercial methane utilization include:

- Electricity production;
- Combined heat and power (CHP) for industry and/or urban areas;
- Commercial natural gas market supply via existing pipelines;
- Local industrial thermal use via local pipelines;
- Spiking natural gas with low quality AMM in volumes that allow the pipeline gas to remain within specification;
- Chemical feedstock;
- Small scale microturbines and fuel cells;
- Vehicle fuel (equivalent to CNG);
- Monetized benefits of reducing greenhouse gas emissions (e.g., flaring).

The most common options for commercial methane utilization are power generation (including CHP) and sale to natural gas pipelines. **Figure 4.1** represents the distribution of utilization options of active AMM projects deployed worldwide reported to the GMI International Coal Mine Methane Projects Database (Global Methane Initiative, 2016).

Each technology option for AMM utilization has its specific constraints, advantages, and disadvantages (**Table 4.1**).

Table 4.1

**General characteristics of selected AMM end-use options**

<i>End use option</i>	<i>Application</i>	<i>Advantages</i>	<i>Disadvantages</i>	<i>Gas quality requirement (% CH<sub>4</sub>)</i>
Injection into natural gas pipeline	High quality AMM (purified)	Equivalent to natural gas, attractive in markets with high gas prices and well-developed pipeline infrastructure	Requires high quality AMM, close to and with access to a natural gas pipeline. If quality constraints are not met will involve costly purification treatment.	95% to 97% methane
Spiking natural gas	Injecting variable and low quality AMM into natural gas pipelines	Facilitates use of low quality AMM that would otherwise be vented	Only low volumes can be added to ensure the natural gas remains within specification limits, AMM price is low and may at best be marginal commercially. Potentially explosive mixtures must be avoided prior to injection.	>25%
Industrial for direct thermal use	Medium quality gas for local industrial and commercial use, and residential district heating	Low cost energy source, minimal gas treatment required, potentially producible on demand	Long-term gas supply volume and quality can be problematic, cost of local pipeline or link to existing industrial pipeline.	>35%
Power generation and waste heat use (CHP)	Gas-engine generators with heat recovery if required	Well-established technology can generate according to demand within limits, potential for peak-opping applications with high tariff, waste heat may be usable.	Capital investment high, only feasible where reasonably high price for electricity, long-term gas flow and quality uncertainty, declining gas resource over time, grid connection can be costly.	>35%
Other uses	Chemical feedstock, CNG and LNG for vehicles, micro turbines and fuel cells	Niche uses, locality and demand dependent.	Generally, will require costly purification, generally taking gas concentrations to pipeline quality or higher CH <sub>4</sub> %	

AMM schemes to date to have principally supplied gas to local industry via a local distribution pipeline or generated electrical power using modular spark ignition engines located on the site. The selection of end use has been driven by local and national energy prices, local market requirements, policy priorities and incentives, transport cost and project investment cost. In the UK, dedicated pipelines have been constructed to supply AMM to industrial users.

Pipeline and thermal use of AMM has many advantages in terms of simplicity of extraction and supply, low capital cost and flexibility of market. Where there is no alternative gas supply available, a premium price may be paid for a clean fuel such as AMM. However, where natural gas supply is readily available, AMM may need to be offered at a lower price to win and maintain market share. Factors influencing the use of AMM as a fuel gas are:

- Gas compression costs for direct injection into a distribution pipe network;
- Permissible gas compositions for injection;
- Proximity of existing pipelines and the need to construct a pipeline network;
- Maintaining minimum gas specification over the supply period;
- Access to alternative fuel source for gas enrichment or back-up supply;
- Access, control and regulation of gas supply to gas grid;
- Availability and need for on-site or down-stream gas storage facilities;
- Proximity of local industrial users;
- Gas treatment needs and cost;
- Land access for pipe network or storage;
- The market for CNG.

If gas quality and production volumes are high and the project is located close to a gas pipeline network, sales to a larger market may be an attractive option. AMM may be sold and transported to commercial pipelines if the produced gas meets certain criteria. Pipeline operators often have very strict gas quality specifications that must be met before gas is permitted to be injected. Concentration limits are established to protect against unconstrained introduction of toxic gases, moisture, carbon dioxide and oxygen. Moisture and carbon dioxide in a pipeline can lead to corrosion, toxic gases could lead to dangerous conditions at the end use site, and oxygen can lead to explosion hazard. While the technology exists to purify the gas to natural gas standards, such a process is unlikely to be commercially viable in many countries.

The gas could also be used in fuel cells and micro turbines to meet site power generation needs or service customers with low power consumption requirements, but these technologies are currently costly due to their generally small-scale.

An AMM utilisation scheme could involve the extraction and use of gas from either a single abandoned mine, or a group of mines. There may also be benefits in linking AMM and coal mine methane (CMM) schemes at active mines. Production of AMM can be varied as required whereas CMM extraction must be maintained to protect the safety of the working mine. AMM could therefore be used in conjunction with CMM to meet peak gas demand. It may also be possible to store surplus CMM in the abandoned mine when demand is low. Multiple

sources of gas offer benefits in terms of improved security of gas supply and opportunities for controlling and maintaining the desired gas purity.

Irrespective of the end use, AMM schemes will require gas to be delivered within specified flow rates and concentrations over the life of a supply contract. Effective management of a scheme will require an understanding of the processes which will cause changes to gas composition, pressure and flow, in particular to the likely impacts of rising mine water levels. Monitoring of water recovery and water levels within the abandoned workings is, therefore, desirable.

The heat value of the gas (upper or lower, adjusted to moisture free, standard temperature and pressure conditions) is the internationally preferred measure of energy supply and should be used as the basis for contractual matters and evaluation of AMM system performance.

Electrical power generation using AMM is generally achieved with reciprocating engines. Advanced fuel management systems and remote monitoring and control systems enable schemes to operate with little manpower. Most schemes are likely to be suited to base load power generation use (24 hours), although, in some instances, advantage can be taken of higher electrical prices for peak generation (peak lopping).

Factors influencing the option to use AMM for power generation include:

- The location, capacity and rating of existing electrical distribution infrastructure;
- Access and connection charges to connect to the national supply grid;
- Costs associated with metering and control to export generated power;
- Power requirements of on-site user;
- Capacity of on-site infrastructure;
- Land and access requirements;
- On-site or local use for waste heat generated;
- Existence of feed-in tariffs or other clean power subsidies.

## 5. Optimizing AMM Production

### *Key messages:*

- Fundamental to the success of AMM schemes is the ability to minimise air ingress into the abandoned workings and control water inflow.
- Engineering measures designed to maximise AMM extraction can be incorporated within a coal mine closure programme, and such measures will be more cost-effective if the work is performed before closure.

### *5.1 Control of Air Ingress*

Control of air ingress will require the effective treatment of **ALL** mine entries connected to the AMM scheme, not only those associated with the mine but any interconnected workings from adjacent mines. It is essential that all entries are identified from mine plans and their surface locations are found and examined.

Mine entries will be either vertical shafts or inclined drifts, ranging from simple excavations with minimal support to sophisticated engineered structures. Treatment options must not only consider the need to form an effective gas tight seal but also ensure ground stability and public safety.

The design of any engineering measures will need to consider:

- Existing infrastructure and shaft/drift construction details;
- Depth to, and geotechnical properties of, rock-head;
- Nature and depth of superficial materials;
- Control of surface water;
- Treatment of service ducts and fan drifts, etc.;
- Removal of shaft furnishings;
- Existing and future surface facilities;
- Working access around mine entry;
- Land ownership and access;
- Future land use;
- Monitoring provisions;
- Maintenance requirements.

The treatment of surface mine entries will require the construction of a shaft cap or drift stopping. Key factors are:

- For shaft seals the most critical design factor is the depth and nature of superficial materials.
- Service ducts and fan drifts should be sealed.
- A drift stopping should be constructed in competent ground and keyed into the natural strata.

- Pipework passing through any shaft cap or stopping should be gas tight, of constant diameter for its full length with no bends and installed to prevent the accumulation of water.
- At least two extraction pipes should be installed through a shaft cap or stopping if these are to be used for AMM production.
- The diameter of pipework should be sufficient to limit pressure drop to a design minimum.
- Safe access to pipework and valves should be provided for monitoring and maintenance.

Engineering options for the treatment of mine entries to facilitate AMM testing and extraction after closure are outlined in **Appendix 3**.

### *5.2 Control of Surface and Underground Water*

Following mine closure, water will rise in the abandoned workings unless pumping is maintained. Rising water levels will fill the abandoned workings, isolating not only areas of un-mined coal (the source of gas) but also the migration pathways created by the underground roadways. The rate of water recovery will vary from mine to mine. A mine could take from a few months to many years to flood completely, depending on inflow rates and the extent of the workings. During the normal working of the mine, information will be collected on the location and quantities of water flowing into the workings, quantities pumped to the surface and areas of workings already flooded.

Engineering measures can be designed and installed as part of the mine closure to minimise the effects of water ingress and to control where water flows. These measures are typically most valuable when there are near-term plans to utilize the methane. They include:

- Measures to minimise surface water ingress through mine entries;
- Placement of clay plugs (or similar) in the shafts or drifts to restrict water flow into the deeper workings via these routes;
- Connecting different mining areas via boreholes, pipework or roadways to control water flow and accumulation;
- Construction of water dams;
- Installation of pipework through low points within roadways to allow for gas transmission;
- The construction of monitoring points to allow water recovery to be assessed;
- Continuation, or installation, of de-watering facilities.

It is important to note that, from an emissions perspective, controlling mine flooding can increase emissions if the methane is not quickly utilized.

Effective management of water recovery as part of the closure programme will involve identifying low points within the main connecting roadways where water may accumulate. Gas tight pipework can be installed through these areas to prevent isolation of adjacent mining blocks even if the roadway becomes flooded. This may be particularly important at



the base of shafts and drifts, or in main tunnels where a blockage may affect a wide area of workings and significantly reduce AMM recovery.

Where possible, advantage should be taken of accessible shafts and drifts for water level monitoring. Use can be made of existing pipework within a shaft, e.g., former compressed air or water ranges.

The installation of suitable monitoring provisions will allow the effects of rising water levels to be assessed and remedial action to be taken, if appropriate. This may involve the drilling of boreholes to specific target horizons. Casing-while-drilling techniques can be used to drill safely through old goaf areas and workings without loss of fluid or incurring hazardous gas emissions.

## 6. AMM Project Development

### *Key messages:*

- Development of an AMM project should entail a series of studies beginning with a basic Desk Study review, followed by a pre-feasibility study and a full feasibility study.
- The Desk Study should rely heavily on available technical documentation but can also include passive or active reservoir testing.
- In addition to more thorough geologic, engineering and operational analyses, the pre-feasibility and feasibility studies introduce policy, market and financial analyses that are necessary to satisfy investors.
- AMM project investors must be convinced that the projected return on investment is commensurate with the degree of risk.
- Once the decision is made to proceed with an AMM project, the next steps are the design, development, construction and operation of the gas extraction and gas destruction/utilization plants.
- The key process design parameters for an AMM plant are the safety of operational personnel, public safety and adequate environmental protection measures.
- Particular attention should be paid to ignition sources and mitigation of explosion risks, but project design and operation should also consider non-hydrocarbon gases including carbon monoxide and carbon dioxide.
- Regular safety audits should be undertaken to ensure that risk management processes are being adhered to.
- Control systems can be monitored remotely such that operational issues are identified in real time allowing plant managers to address problems quickly.

### *6.1 Desk Study Review*

Vital information on the AMM reservoir will be contained within mining records, reports and plans. The reservoir can be described as a series of discrete “stacks” of coal seams de-stressed by previous longwall mining. These worked areas are interconnected internally within an individual stack by the district roadways, which in turn are linked to the main mine roadways and back to the pit bottom area, and finally to the surface. The amount of de-stressed coal in any stack will vary as will the condition and transmissivity of roadways and goaf connections. Testing and analysis enable the composite characteristic to be determined. Key factors required to develop a description of the AMM reservoir are:

- Mining methods used and the likely vertical extent of the gas reservoir;
- The volume of de-stressed coal and number of individual stacks comprising the gas reservoir;
- The type and properties of intervening strata between coal seams;
- Potential sources of gas, additional to coal seams;
- Coal properties and gas content;
- Water flows and sources;
- Waterlogged areas prior to closure;

- Low points in the main mine roadways where water could accumulate and cause blockages;
- Underground connections to other mines;
- Main underground connections between different working horizons;
- Connection to shallow surface workings and potential air ingress;
- Potential for unrecorded workings and mine entries as possible sources of air ingress;
- Number of mine entries and scale of engineering required for minimising air and water ingress;
- Existing gas production operations.

The critical reservoir characteristics in terms of water ingress, flow and likely mine water recovery scenarios need to be identified together with the potential for air ingress. Suitable locations for connecting to the abandoned workings for extraction can also be determined, either involving a shaft, drift or purpose drilled borehole. Where existing shafts or drifts are unsuitable, perhaps because they have been filled, a borehole will be necessary. A common practice is to drill AMM extraction boreholes to intersect roadways in generally stable areas where a good connection to the network of abandoned workings is likely to be achieved.

### *6.2 Reservoir Testing*

The desk study review is used initially to develop a 3-dimensional conceptual model of the reservoir. However, uncertainties will remain on key issues that will determine maximum production rate, total recoverable volume and gas quality including:

- Water levels and recovery;
- Potential open mine void;
- Potential air ingress through surface entries;
- Connectivity between the surface extraction point and the reservoir;
- Transmissivity of the underground reservoir.

It is, therefore, good practice to monitor gas concentrations and flows naturally emitting from abandoned mine entries (passive testing) and perform gas pumping tests (active testing) to confirm the commercial viability of the reservoir. A range of tests and possible interpretations are summarised in **Appendix 1**.

Active testing can only be done if all the mine entries have been sealed to a reasonable standard. Test pumps can be connected to an existing vent pipe. In the absence of a suitable connection, a test borehole must be drilled to intersect the workings. Gas pumping tests will enable the reservoir flow characteristics to be determined. These tests provide information on the flow resistance between the surface extraction point to the underground workings, the magnitude of air ingress, the equivalent resistance of the interconnected mine roadways and mined-out longwalls (goaf areas), the effects of mine water recovery and potential gas composition and flow. Results from field tests need to be considered in conjunction with the evolving model of the AMM reservoir and not in isolation, otherwise erroneous interpretations could be made and the design of a scheme compromised.

### 6.3 Pre-Feasibility Study

A pre-feasibility study will be required to reassure potential investors that the proposed project makes financial sense and that the principal technical and administrative factors that could affect the outcome have been identified. The pre-feasibility study should include plans showing the key information to help newcomers to the project arrive rapidly at a clear understanding of what is proposed. Quality data will reduce uncertainties. Historical and up-to-date monitoring data of key factors, in particular, gas content, emissions during mining, water ingress and locations, and water levels are essential. Support for a project will ultimately depend on its financial and technical merit.

A pre-feasibility study will involve undertaking a basic geological and mining review of the coal mine and a high-level market assessment and basic financial analysis. As part of the market and financial analysis, a pre-feasibility study should attempt to identify incentives and other incentivizing policies along with possible disincentives. To the extent practical, it is beneficial to quantify potential costs and benefits of policy mechanisms. The elements that should be included in a pre-feasibility are listed in **Appendix 2**.

### 6.4 Full Feasibility Study

While a pre-feasibility study provides an initial assessment with some site-specific data, a full feasibility study is advisable and often necessary to finance a project. A feasibility appraisal might involve, among other tests, connecting an extraction pump to an already sealed mine to determine the production characteristics of the AMM reservoir. Engineering works may therefore be required to seal the mine entries or to improve the standards of existing seals. As significant capital expenditure can be incurred, this stage is only undertaken if the pre-feasibility study indicates promise.

The principle elements of a feasibility study are:

- Construction or enhancement of mine entry seals and production pipework;
- Passive gas testing (naturally vented flows and gas compositions);
- Pump testing (pressure trends, flows and gas compositions produced at a range of extraction rates);

#### **Box 3. Investment ready AMM projects are those where:**

- Significant reserves have been identified with an expected project life of 10 years or more;
- The project aims are clearly defined, understood and achievable;
- Gas ownership is clear, and the developer has the production rights;
- A management structure and key decision-makers have been identified;
- Local government approvals and support (including financial) have been obtained;
- Technical risks are quantifiable and controllable;
- Suitable technology is selected and applicable to the skills base of the community;
- Revenue can be generated at an early stage;
- Customers have been identified and firm supply contracts negotiated;
- Significant environmental and social benefits will accrue;
- Payback of capital is possible in 2 or 3 years;
- There are long-term gas use/sales prospects.

- Analysis of passive and active monitoring results;
- Remedial and investigative work as required on mine entry seals and any other leakage paths;
- More detailed geologic review;
- Detailed designs and costings for a full extraction and utilisation scheme;
- Market study;
- Legal and regulatory analysis;
- Financial evaluation.

### *6.5 Financing AMM Projects*

A pre-requisite for an AMM project seeking funding is that it meets the technical criteria that will allow for delivery of the projected revenue, which is usually established in outline by pre-feasibility assessment and in detail by a full feasibility study. An important consideration in assessing feasibility of projects is the regulatory environment, described in more detail in **Chapter 7**. Policies and regulations can affect payback and profitability prospects by determining taxation and fiscal incentives, as well as by reducing the administrative burden that companies face in relation to obtaining ownership rights or gaining access to infrastructure. In some instances, environmental, political and social drivers may also play an important part.

Investors in a potential AMM project need to be convinced of the following:

- That all necessary approvals are in place, especially regarding AMM production rights;
- That it is a sound technical project;
- That there is a market for the gas and that buyers are prepared to pay a reasonable price;
- Project documentation is clear and transparent, and the project's aims are clearly defined, understood and achievable;
- That the project is of a sufficient scale to justify the effort required in structuring financial arrangements and administration;
- That technical and financial risks associated with the project are quantifiable and controllable;
- That the projected return on investment is commensurate with the degree of risk;
- The timing and certainty of cash flows.

Where there is scope for replication of projects, investors may be willing to accept smaller margins for the first project in the knowledge that the experience gained will result in reasonable returns from subsequent projects.

Various financial incentives may be available, which can increase the attractiveness of AMM projects to investors as described in **Chapter 7**.

Additional information on financing mine methane projects can be found in U.S. Environmental Protection Agency's *Coal Mine Methane (CMM) Finance Guide*.<sup>7</sup>

### *6.6 AMM Project Design and Operation*

Once the decision is made to proceed with an AMM project based on a sufficient evaluation of the technical and economic merits of the project, the next steps are the design, development, construction and operation of the project.

#### *6.6.1 Key Design and Operational Parameters*

During active coal mining operations, underground coal miners' safety is the key design parameter for any gas extraction and destruction/utilisation plant. This focus changes after mine abandonment as the site evolves to a surface only operation. Like with most industrial operations, the key process design parameters for the AMM plant are the safety of both: operational personnel and the people who may live close by or visit/trespass the site, as well as environmental protection measures including management of emissions, stormwater runoff, and proper disposal of industrial waste.

In general, the safety of the installation is split into two parts: the gas safety associated with the mine void space (i.e. how the gas can escape from the mine) and the process safety of the gas extraction and destruction/utilisation installation.

The main hazards are associated with the potential for fire or explosion from the mine methane.

Whenever engaging in the design for such a plant, an initial investigation must be carried out to determine what statutory regulations (local laws) are applicable to the plant. This includes determining parameters to ensure compliance with local zoning and permitting requirements.

Environmental compliance is also strictly enforced in many countries and should be a priority for any AMM project site to comply with regulatory requirements and to demonstrate sound environmental stewardship. At a minimum, site construction and operation should minimize airborne emissions of pollutants and dust, engage in proper waste and wastewater disposal, effectively control stormwater discharges, and protect groundwater resources. Depending on site location, care should also be taken to limit the impact on flora and fauna.

After considering safety, health and environmental protection from a general and regulatory perspective, specific design criteria must be considered.

#### *6.6.2 Specific Design Criteria*

- Compliance with local laws and regulations;
- Compliance with local permit requirements;
- Mine void space gas integrity (verification whether there are any gas leaks from the mine void around the shaft, or whether they are likely in the surrounding geology, or, if under vacuum, whether there is air ingress into the mine);

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<sup>7</sup> U.S. Environmental Protection Agency (USEPA). Coal Mine Methane (CMM) Finance Guide (Updated July 2019). EPA-400-D-09-001. Washington, D.C., July 2019. [https://www.epa.gov/sites/production/files/2016-04/documents/cmop\\_finance\\_guide\\_march\\_2016\\_revision.pdf](https://www.epa.gov/sites/production/files/2016-04/documents/cmop_finance_guide_march_2016_revision.pdf)

- Location of mine void space leaks (points of escape or air ingress);
- Security of site and installation, including fencing, warning signs, detectors and remote alarms if unmanned;
- Local residential housing or industrial facilities and their impact on the facility design;
- Gas well design, including venting and isolation facilities;
- Venting facility design (including radius of hazardous area);
- Gas pipework design;
- Water drainage facilities (usually simple water knock out pots, or cooling heat exchanger with water cooling circuit or air radiator fan);
- Extraction plant design;
- Destruction or utilisation plant design;
- Remote monitoring system;
- Earthing (grounding) and lightning design;
- Noise design;
- Civil design;
- Electrical connection for supply and possibly network export;
- Gas export connection;
- Process safety risk assessment;
- Operational safety risk assessment;
- Environmental risk assessment.

The list above presents a high-level summary of the design considerations for an AMM plant. This section provides below further guidance on specific high-priority items.

### *6.6.3 Lightning Design*

Lightning is a proven and regular source of ignition for flammable gas mixtures at both operational and abandoned mines. Equipment should be properly earthed (grounded) in compliance with local regulations and power isolation trips incorporated as necessary.

Due consideration should be given as to whether the plant facilities are connected or separated from an earthing (grounding) perspective from the wellhead or mine connection.

### *6.6.4 Flame Arresters*

One of the key design features of abandoned mine methane extraction and utilisation plants are the use of flame arresters within gas pipework to prevent flame propagation. Flame arresters are designed to temporarily impede the path of a flame front through a flammable gas-air mixture. When selecting a flame arrester, it is imperative that a competent specialist engineer is used to ensure that the correct design of arrester is installed. Depending on the source of ignition and the position of the arrester, different types may be required.

Flame arresters are normally used with automated systems that measure temperature on the protected side, automatically coupled with an actuated isolating valve to cut off gas flow to the arrester and extinguish the flame.

### *6.6.5 Gas Analysis and its impact upon Safety, Monitoring and Measurement*

Methane concentration is monitored around the AMM plant for several reasons. Personal gas detectors are used by plant operators to ensure their safety and as a back-up to detect any methane leaks. Fixed gas detectors are installed in buildings to detect uncontrolled escapes of methane, often supplemented by smoke and carbon monoxide sensors to detect fire and products of combustion. Within the gas pipework, transducers for flammable gas concentration and oxygen are normally installed to ensure explosive mixtures are not being transported. To ensure high levels of safety, redundant instruments may be appropriate. Where financial incentive is involved, accuracy and reliability of gas readings will be important. On safety critical installations, detection and process response will need to be rapid.

In addition to methane, ethane and propane, also other alkanes may be present, increasing the calorific value of the gas and the flammability range of air-gas mixtures. Infrared detectors commonly used for methane monitoring are cross-sensitive to ethane, which if not recognised can give rise to false high methane readings.

If the flammable range is important to the destruction or utilisation process, then Le Chatelier's principle can be used to correct the flammability range. By increasing process' methane pressure or temperature, the flammable range will also widen, in particular the upper limit will be raised. This is important if there is air present in the AMM mixture and if it is being compressed. In general, the flammable gas content of the gas is expressed using the term "percentage methane"; for example, a gas with 20% nitrogen and 80% flammable gas would be described as 80% methane.

Coal mine gases are water-saturated and warm, and hence gas detection and sampling devices need to be designed to avoid accumulation of condensate either by drying, decanting or heating. In addition to methane, carbon monoxide (a low temperature oxidation product and a result of underground mine fires), carbon dioxide and nitrogen are invariably present in AMM.

### *6.6.6 Extraction Plant Design*

An extraction plant is required to draw gas from the abandoned mine void space to the surface and for transporting the gas under pressure toward the destruction or utilisation plant. Generally, at AMM installations, extraction plants are either of the dry type, where positive displacement blowers, fans or centrifugal compressors are used, or the liquid ring vacuum type, when the extraction plant is inherited from operational mining. Liquid ring pumps have the advantage that they can achieve greater vacuum suction levels than dry pumps. However, they have a maintenance intensive water seal cooling circuit, and may have higher parasitic electrical load demand when compared to dry systems. Another disadvantage of liquid ring pumps is that they deliver to the utilisation plant gas that is completely saturated with warm water from the water-seal system, and with chemical contaminated water from the water-seal cooling system.

The gas extraction plant can be accommodated in former mine buildings, but it is more commonly located within modular containerised enclosures, which can be easily relocated to other sites, as the AMM reservoir source becomes depleted.



#### *6.6.7 Gas Destruction or Utilisation Plant*

From an environmental perspective, the design hierarchy should be utilisation, destruction, and in the worst case, venting. This hierarchy could also be applied from a safety perspective, with utilisation and destruction having a similar safety profile, because the gas is combusted in an enclosed and controlled manner; but with venting being the worst case, as it allows a flammable air/gas mixture to be released to the atmosphere with the potential for ignition. However, flame traps will prevent any transmission of flame into the abandoned mine. Venting sites should be securely fenced and, if possible, located remotely from residential areas. Flame traps will require regular servicing and unattended sites should be inspected regularly to assure their security.

#### *6.6.8 Utilisation Plant Commercial Risks and Resource Assessment*

Other than a secure source of reliable and sufficient revenue, the primary factor impacting the commercial success of an AMM project is the accurate estimation of the gas resource and appropriately matching the estimated gas resource to the sizing of the extraction and utilisation plant. Computer based modelling can be used for void space estimation and gas production forecasting, but generally the further step of draw-down testing generates much more reliable void space resource data at the pre-investment project design stage.

AMM technology generally involves use of well-proven equipment, some of which may have been developed for coal mine methane or landfill gas extraction and utilisation projects.

Use of containerised semi-mobile extraction plant and utilisation plant allows for easy relocation in the event of unexpectedly poor AMM recovery at a site, thus mitigating commercial risk, provided that there are alternative AMM sites available. The larger the portfolio of abandoned mines, the more efficient is the use of semi-portable extraction and utilisation infrastructure assets. For example, at a company with AMM projects at five mine sites, if one mine under-delivers gas, the assets can be moved to another mine that is generating more gas than expected.

#### *6.6.9 Operation and Maintenance*

Operation and maintenance of extraction and utilisation plants are carried out by general operators with semi-skilled staff, but with mechanical and electrical specialists on call as required. Maintenance of gas-engines and generators may also require specialists trained by the equipment suppliers.

Regular safety audits are required to ensure regulatory compliance and maintenance of operational standards, as well as to assess training or refresher needs.

#### *6.6.10 Remote Monitoring*

Generally, AMM sites are unmanned and monitored remotely either by the project owners or by contractors. Extraction systems and destruction/utilisation systems are usually controlled using programmable logic controllers (PLC) and are generally connected remotely to either a central control system or to operator/management PCs. GSM or cell phone data connections can also be used where installations are remote from hardwired internet networks. Automated alerts can notify operators and managers when the plant cuts-out due

to a defect or out of range gas parameters. The security of unmanned sites can be protected with the help of intruder alerts and remote cameras.

The range of possible equipment and service needs are summarised in **Appendix 4**.

## 7. Policy and Regulatory Mechanisms to Facilitate and Promote AMM Extraction and Use

### Key messages:

- It is essential that policy and regulation promote maximum extraction and use or destruction of AMM emissions.
- Experiences from several countries provide valuable lessons for other countries wishing to utilize the potential of AMM.
- Clear and practical AMM ownership rights are critical for successful deployment of AMM projects.
- Regulations that direct mine operators to engineer and install recovery systems for future gas recovery after abandonment can encourage more AMM projects and further reduce emissions.
- In addition to healthy energy commodity markets, reduced taxes or targeted financial and fiscal incentives can stimulate AMM projects.
- Carbon markets can also drive AMM project development.

### *7.1 Role of Mine Management in Preparing for Mine Closure*

Good practice policies could create a framework that encourages a mine owner to collaborate with an AMM developer to ensure a mine is engineered to facilitate AMM production during the closure process. For example, an attractive subsidy or a value for the GHG emission reductions could make an AMM project financially viable, providing a revenue source for both the mine owner/operator and the AMM project developer.

Policies should also include a mechanism for avoiding or resolving disputes between working mines and adjoining AMM producers where interactions occur.

### *7.2 Gas Ownership*

Clearly defined ownership rights can help companies mitigate risks in AMM projects. Likewise, transferring ownership of AMM to a third party reduces the project's financial risk in certain situations, and allows the resource to be developed. Countries with successful AMM projects have created an enabling environment by eliminating restrictions on transferring rights to the gas, regardless of whether it is sold as gas or converted to electricity (**Table 7.1**).

Addressing mine ownership concerns might require examining legal treatment of AMM. For example, in Kazakhstan, the Subsoil Law distinguishes all reserves as commercial ('on-balance') and non-commercial ('off-balance').<sup>8</sup> At the moment, the law views AMM as a waste, non-commercial resource and does not offer guidance on how entities could obtain rights to this 'off-balance' resource. Recently, Kazakhstan has declared its intent to adopt the classification standard used by most OECD countries, i.e., CRIRSCO, developed by Committee for Mineral

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<sup>8</sup> This classification is unique to the countries of the former Soviet Union and does not have exact equivalents in international classification standards of mineral reserves. For a more detailed description of various classifications, see Weatherstone, 2008.

Reserves International Reporting Standards. This could potentially simplify procedures for obtaining and transferring rights to the AMM resource.

Table 7.1

**Methane ownership**

<i>Country</i>	<i>Ownership of gas</i>
United States	Federally and privately owned - AMM projects typically need to acquire methane gas rights, and procedures vary by state and surface owner.
France	Owned by the government - Concessions are granted to operators, but some existing surface equipment that were installed for safety purposes, such as wellheads, belong to the government. Use of these government facilities are permitted for use by concession owners on a case by case basis.
Germany	Federally owned - Procedures to obtain AMM rights are simple and streamlined.
United Kingdom	Government owned - AMM production and use requires a Petroleum Exploration and Development License or Methane Drainage License.
China	State owned - The situation for AMM is unclear. Coal and CBM are licensed separately. CMM use does not require a CBM license.
Ukraine	Government owned - Ukraine has no AMM projects today, but rights to the gas would likely be leased, as CMM and other gas rights are.
Australia	State owned - state and federal governments consider AMM a petroleum product. State rules vary, but in all cases, AMM developers must get a petroleum license.

*Sources: USEPA, 2019; and Denysenko, A., et al., 2019; Modified from Coté, M., 2018. Emissions and preparing for projects, Global Methane Forum, UNECE side-event, Toronto, Canada, 16 April 2018*

**7.3 Fugitive Gas Liabilities**

An AMM operator could reasonably be required to exercise specific design measures on termination of a project to leave a site in a safe condition. A positive benefit of AMM extraction is that operation of the scheme will have led to a lower surface emission risk situation than if the scheme had not been constructed. However, if policies place long-term liability on AMM operators, this will disincentivize projects.

**7.4 Infrastructure Access**

AMM projects are typically only viable when they have easy access to natural gas and power markets. Without easy market access, projects must use the methane on site or locally, and the demand and price usually make this uncompetitive. Thus, market access is a critical policy issue.

At the same time, AMM must be transported and used in a safe manner. A key principle is that gas mixtures in or near the explosive range (5 - 15 percent CH<sub>4</sub>) should not be transported in pipelines or used in power production.

### *7.5 Financial and Fiscal Incentives*

Incentives to help finance methane utilization projects include tax credits, reduced royalties and clean power incentives (e.g., as in Germany and several U.S. states). For example, in the UK, AMM projects are exempt from the Climate Levy. In Germany, AMM projects can access favourable “market premiums” when the methane is used to generate power. Several U.S. states also provide reduced royalties for AMM produced on state land. At least one company in France has been guaranteed a feed-in tariff for electricity generated from AMM as long as the concession license is in force (Moulin, 2019).

### *7.6 Carbon Finance*

Carbon finance has been proved an effective market-based instrument to trigger CMM projects (UNECE, 2016) under the Clean Development Mechanism (CDM) and the California Air Resources Board (CARB), and could equally well support development of AMM projects where applicable. Establishing clear methodologies can help facilitate carbon finance and reduce project risk. Methodologies provide clear rules on what types of projects can qualify and how the emission reductions will be estimated, which is essential information for project developers to determine whether a project is viable.

The Clean Development Mechanism (CDM) implemented under the Kyoto Protocol from 2008-2012 allowed developed countries to develop and claim Certified Emission Reductions (CERs) or Emission Reduction Units (ERUs) from application of approved methodologies in developing (non-Annex 1) and developed (Annex 1) countries, respectively. The CDM mechanism stimulated the development of 128 CMM projects approved by the NDRC in China from 2005-2012. Not all projects qualified for CERs, and the price for CERs dropped precipitously after 2012 due to lack of demand from the European Emissions Trading Scheme (ETS), the only sizeable market for the credits. Nevertheless, the CDM incentives have enhanced development of the CMM industry throughout China, bringing international investment, improved gas drainage and advanced methane utilisation technologies. However, since 2012 new CDM projects can no longer be registered in China. The UNFCCC approved CDM methodology for CMM use and destruction (ACM0008 version 08.0) also extends to AMM and it is possible that AMM offsets could become applicable under a national China ETS. However, to date, there have not been any registered CDM AMM projects.

The California Cap-and-Trade Program under the control of the California Air Resources Board (CARB) provides covered entities, such as power plants, allowances to emit GHG gases. CARB has recognized AMM emission reductions as a qualifying offset type as long as the project follows the Mine Methane Capture Projects Compliance Offset Protocol.<sup>9</sup> This protocol applies to U.S. underground, surface and abandoned mines. As of July 2019, five AMM projects have received California offsets under this methodology.

There are also various international voluntary GHG programs for registering emission reduction projects, but the markets for these are small, prices are low, and coal mine-related emission reductions can be difficult to sell.

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<sup>9</sup> <http://www.arb.ca.gov/cc/capandtrade/protocols/mmcprotocol.htm>

## 8. Summary and Conclusions

Abandoned mine methane is part of the coal mine emissions lifecycle that in some instances can extend for decades after mining ceases. AMM has favourable characteristics for use and it can generally be produced at 15% - 90% methane, and with virtually no oxygen, if a gassy coal mine is sealed well. The characteristics differ from CMM production in that, that gas availability decreases with time as the gas remaining in the coal reservoir becomes depleted. However, an AMM reservoir with a significant biogenic component may not necessarily show similar depletion characteristics. The volume of extractable gas can be further shortened as the groundwater system recovers and progressively floods a mine which prevents gas desorbing from the coal and also potentially compartmentalizing the mine to restrict gas transmission from source to production point.

Not all abandoned coal mines will be suitable for AMM extraction.

In general, AMM projects tend to be 10-25% the size of CMM projects at the same mine but abandoned mines can be aggregated into a single larger project. However, there are sites in Europe where AMM extraction has matched CMM flows when the mine was active, and even some where AMM production exceeds former CMM production (Backhaus, 2018). The latter situations may arise where recent biogenic methane has been generated in addition to fossil methane and where natural gas migrates into the void from other strata through time.

AMM projects are simpler than CMM projects, since production is not driven primarily by safety considerations as mine operations have ceased. However, this advantage might be offset in mines that have not been prepared for AMM recovery before closure and in which local flooding of the workings, as well as inadequately engineered entries hinder gas transmissibility from the reservoir, resulting in poor production rates and low gas quality.

Issues to consider when closing a mine with AMM production potential include:

- Accessing the underground workings for gas extraction from shafts or drifts;
- Installing gas piping underground to connect sealed parts of the mine to the extraction point, and through areas of roadway dips where water might accumulate and block connectivity;
- Using the mine roadways as conduit for gas flow;
- Verifying integrity of surface seals to prevent atmospheric air leakage.

Policy framework is also an essential element for project viability. Key issues include ownership rights, ability to transfer those rights, access to incentives such as those for renewable power, as well as tax and royalty benefits, and policies to ensure that mines are sealed to preserve AMM for projects.

Focusing on the importance of methane rights, AMM projects undertaken by third parties can be complicated by the need to apply for new licenses or permits. In some countries there is a lack of clarity on surface and underground ownership of abandoned mines, as well as of gas rights, thus deterring investment.

Successful AMM recovery and utilisation projects offer several benefits:

- They provide energy from a resource that would otherwise be wasted by emission to atmosphere.
- They provide an environmental gain by preventing the release of methane which is 28 to 34 times more potent a greenhouse gas than carbon dioxide.
- They provide an additional environmental gain by replacing a more polluting fuel such as coal, which may otherwise have been used.
- Depending on local conditions, power from AMM schemes may be competitive with available alternatives.
- They provide additional investment opportunities through eligibility for inclusion within carbon offset mechanisms, where applicable.
- They provide employment opportunities in former coal mining areas.
- They protect against uncontrolled methane leakage at the earth's surface, which would constitute a hazard to the public.

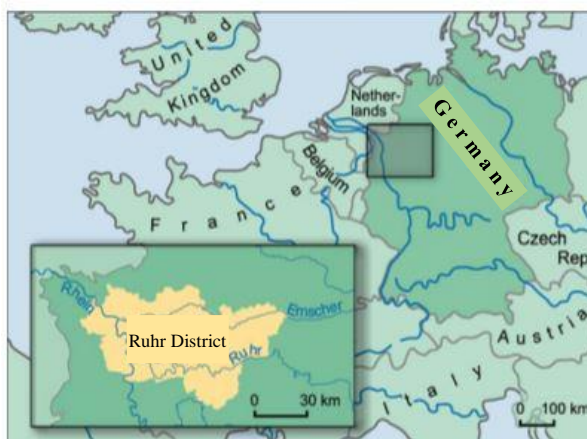
## 9. Case Studies

### Case Study 1: Germany - Ruhr Coal Field, North Rhineland Westphalia

The Ruhr Coal field was once the largest and one of the most important coal producing areas in Europe (Figure 9.1) (Dodt & Drecker, 2018), with its first deep hard coal mine opening in the 1820s. At its peak in 1850 there were almost 300 coal mines operating in the area, with mining employment peaking in 1956 with over 600,000 workers. However, the industrial mining of hard coal in Germany came to an end after almost 200 years with the closure of the Prosper-Haniel mine in Bottrop in early 2019.

Figure 9.1

#### Location of the Ruhr Coal District



Source: Dodt, J., M. Drecker, 2018

In order to facilitate the transition away from fossil fuels to renewable energy sources, Germany established the Electricity Feed-In Act In 1991, which was the first green electricity feed-in tariff scheme in the world. This Act was replaced in 2000 when Germany passed the Renewable Energy Sources Act (EEG), which while modified several times over the years, comprised a series of laws that provided feed-in tariffs to encourage the generation of renewable electricity. In 2014 and 2017, the laws were modified so as to facilitate transition of all renewable energy projects away from feed-in tariffs and toward an auction system.

Between 2002 and 2004 project developers, taking advantage of the EEG, established AMM projects at several of the gassier coal mine sites in the Ruhr valley (Table 9.1).

Table 9.1

#### Select AMM Projects in the Ruhr Valley

Coal Mine	Years of Mine Operation	Ave. Annual Coal Prod. (MT)	Methane Explosions When Mine was Active	Power Generation Site	Installed Capacity (MW)	Total Elec. Output (GWh)	Years of Operation	Emission Reductions (tCO <sub>2</sub> e)	Comments
Lohberg	Shaft 1: 1909 - 2005 Shaft 2: 1909 - 2005	1.3 - 2.5		Lohberg	7 x 1.3	510.4	2002 - Present	1,861,028	Mine is not totally sealed, air incursion contaminates AMM.
Niederberg 1	Shaft 1: 1912 - 2002 Shaft 3: 1954 - 2001	2.0 - 2.8	1 explosion-3 deaths	Neukirchen	4 x 1.3	494	2004 - Present	1,802,470	Mine is sealed, no obvious air incursion.
Minster Achenbach	1897 - 1992	0.13	5 explosions-117 deaths	Christemark	1 x 0.4 1 x 1.0	25.8	2003 - 2007	141,030	Mine is flooded, which limited available AMM.
Dorstfeld	1859 - 1963	0.85 - 1.1	2 explosions-12 deaths	Wilberd	0.2	25.1	2001 - Present	91,855	Outgassing into houses occurred during mining; AMM production and flooding have ceased this, but AMM is limited.
Lothringen	Shaft 1: 1872 - 1967 Shaft 2: 1895 - 1967	1.1 - 1.4	1 explosion-115 deaths	Corvin 1	4 x 1.3 1 x 0.6	96.8	2004 - Present	352,940	Many abandoned shafts located nearby that are not sealed, causing contamination of AMM production.
Erin 6	Shaft 1: 1887 - 1983 Shaft 6: 1943 - 1983	1.1 - 1.4	2 explosions-6 deaths	Corvin 2	1 x 1.3	207.8	2004 Present	757,638	

Source: Marshall, J., 2019, data provided by Mingas-Power GmbH and A-TEC Anlagentechnik GmbH



At each mine site, gas recovery projects were constructed utilizing one or more Deutz landfill gas generator sets, fueled by abandoned mine methane drained from the mine's void to generate electricity for sale to the local grid (**Figure 9.2**). The emission reductions reported in the table are attributed to those total reductions associated with supplanting coal-fired power with gas-fired power over the project life. Each project's reported emission reductions include both the grid emission reductions attributed to the electricity sold to the grid supplanting coal-fired power, and the emission reductions associated with the destruction of abandoned mine gas used to generate the electricity.

Figure 9.2  
**Lohberg Power Generation Station**



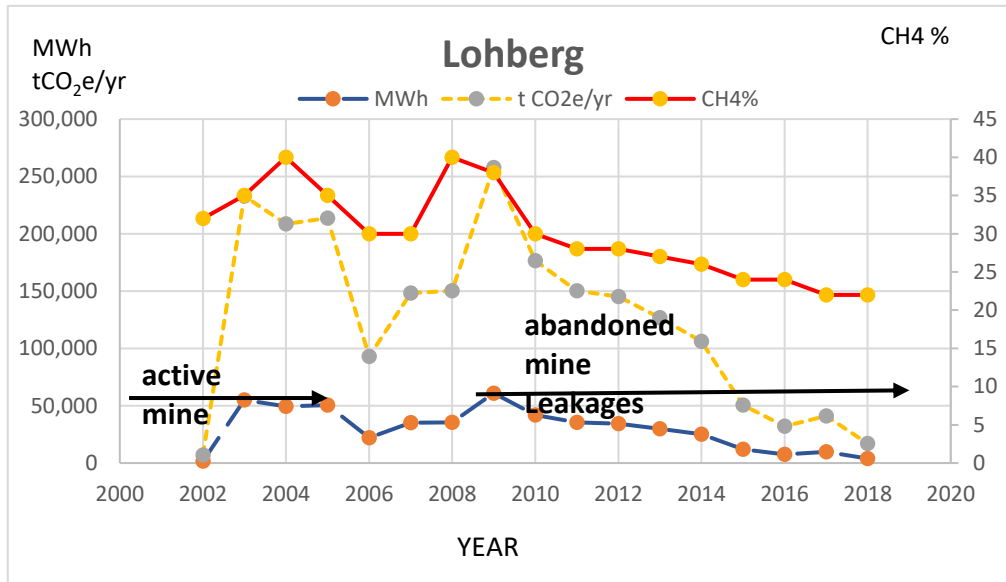
Source: Mingas-Power GmbH

The German Federal Mining Act recognizes that mining activities do not end with mine closure, requiring the mine operator to provide a specific abandonment plan to rehabilitate the site which must be approved by the Mining Authority before the mine permit is relinquished. The gas-filled void space of many of the mines remains in communication with the atmosphere. Due to inadequate sealing of many older boreholes and shafts, uncontrolled increases in gas pressure can cause gas to migrate into aquifers, buildings, and other structures located at the surface above the abandoned mines. Pipes which are used for degassing the void are installed in the filled-in shafts so that gas produced from the underground void can escape through the degassing pipes, reducing the uncontrolled gas migration at the surface. In addition to uncontrolled leakage of mine gases to the atmosphere, the lack of reliable seals causes the concentration of abandoned mine gas to fluctuate during production. Further exacerbating this issue is the fact that many of the Ruhr District mines are connected underground and gas extracted from the gassier mines is often further diluted by air from less-gassy mines. Project developers have learned that if the suction pressure of the vacuum pumps is not managed, gas concentration will decline over time, which negatively impacts the project's operations and economic success. An example is depicted in **Figure 9.3** which clearly indicates that the shafts of the Lohberg mine have not been completely sealed. As power production operations begin at the abandoned mine and suction was applied in 2009, air was pulled into the mine

diluting the mine gas. By the following year the methane concentration had decreased further. The trend continued in subsequent years and methane concentration reduced from around 40 per cent in 2008 down to 25 percent by 2018. As the decrease in the concentration of methane in the produced gas continues over time, the efficiency of the genset is negatively impacted, thereby reducing the amount of electricity generated.

Figure 9.3

**Lohberg Electricity Output and Methane Concentration Plot**



Source: Mingas-Power, A-TEC Anlagentechnik

### *Case Study 2: Poland - Upper Silesian Basin*

Since 1989 about 40 coal mines have been closed in Poland. The majority of these mines are virtually non-gassy. Of the remaining few gassy closed mines, two have had AMM utilization projects. It is worth mentioning that the recently closed mines are gassy and the majority of active mines are gassy, so there is good potential for future AMM projects in Poland.

#### *Morcinek – Kaczyce Mine*

Years of mine operation: 1986 - 2000

Geologic information: Average seam thickness of mined coal seams ranged from 1.32 m to 1.44 m and their mining depth from 950 m to 1100 m. The age of coal measures is Upper Carboniferous (Numurian-Westphalian) and the maturity of coal is HVBA-MVB (ASTM standards). The coal seams were structurally complicated and difficult to mine.

Gas emissions: relative daily emission rate (gassiness) was 30 m<sup>3</sup>/t during coal mining.

Mode and volume of gas production: AMM is produced by one well drilled from surface to the gob area at the depth of 680 m. Gas production started in 2001 and the annual methane production as of the end of 2017 was 2.29 MMm<sup>3</sup>.

End use: The main end user is the Green Gas DPB in Paskov, Czech Republic and the gas is transmitted via pipelines.

#### *Żory Mine*

Years of mine operation: 1979 - 1998

Geologic information: The mined coal seams were relatively thin, rarely exceeding 2 m in thickness, and the mining depth was from 400 m to 830 m. The age of coal measures is Upper Carboniferous (Westphalian) and the maturity of coal is HVBB - HVBA (ASTM standards). The maximum gas content of mined coal seams was 12 m<sup>3</sup>/t(daf).

Gas emissions: relative annual emission rate (gassiness) was 10.5 – 54.0 m<sup>3</sup>/t of mined coal during the coal mining; absolute emission rate ranged from 46 m<sup>3</sup>/min (in 1987) to 18 m<sup>3</sup>/min (in 1996). Total amount of methane released during the coal mining was 256 MMm<sup>3</sup>.

Mode and volume of gas production: AMM has been produced by means of surface wells drilled to the gob area within the Żory mine and to the gallery within the adjacent, undeveloped coal field called Jankowice-East, which is connected with the Żory mine workings. The first well drilled within the Żory mine area, to the depth of 209 m, was put on production in 2012; its recent annual methane production as of the end of 2017 was 3.25 MMm<sup>3</sup>. Another production well was drilled to the gallery within the Jankowice-East coal field in 2013; its recent annual methane production as of the end of 2017 was 1.93 MMm<sup>3</sup>.

End use: power and heat generation using gas engines.

#### Encouraging policies or incentives for AMM in Poland

There is no royalty payment for coalbed methane production (including AMM) and the payment for purchasing the government owned geological data which are used for CBM development is only 10 percent.

There is a national trading scheme for violet certificates used for supporting electricity and heat producers exploiting mine methane or gas generated by the biogas plants. However, this

type of support may include AMM only if the operator produces energy in cogeneration using highly efficient CHP units, enabling primary energy savings at an appropriate level.

In 2018 a new regulation was introduced concerning the use of AMM, which allows the government owned Mines Restructuring Company (tasked with closing mines) to recover AMM without a license during the mine abandoning process, as long as it is justified by safety and environmental concerns. This regulation has filled the gap in the law, as previously methane emitted after cessation of coal production had to be vented to the atmosphere, for there was no regulation allowing for methane utilization activities.

#### Lessons learned and conclusions

In spite of the above-mentioned incentives, only two AMM utilization projects have been conducted in Poland so far. The main reason is a long and complicated permitting process for AMM recovery. In Poland AMM is treated by the Geological and Mining Law as any other natural gas deposit. Therefore, all requirements concerning a hydrocarbon license process have to be fulfilled, which is time consuming and costly. Furthermore, since the mine abandoning process has to be completed before investors can apply for a CBM production license, there is an additional time delay in the commencement of an AMM utilization project. As methane emission from abandoned mines is expressed by a hyperbolic decline curve, the AMM reserves could be significantly depleted after a few years needed for all the abandoning works to be completed.

Also, the level of support obtained from the use of violet certificates is considered to be insufficient for AMM utilization as it is primarily aimed at the coal mines recovering CMM as a byproduct of coal mining (due to safety concerns) assuming zero cost, whereas substantial cost has to be incurred in AMM recovery.

In light of the above comments, changes in the law should be initiated.

### *Case Study 3: UK - Abandoned Mine Methane Utilization in the United Kingdom*

Since 1952 approximately 1,300 underground mines have been closed, and in more recent years since 1979, around 130 underground mines have been closed. During the mid-1990s Alkane Energy pioneered abandoned mine methane utilization within the United Kingdom (UK), either drilling into sealed mine-workings, or entering capped shafts with around 15-20 projects (current projects' installed capacity at 43MWe). In 1998, the main UK underground coal mining company, UK Coal Mining, started to follow Alkane's example and commenced installation of mine gas utilization plants across their gassy operating mines, completing six projects. As the mines closed, some of these projects transitioned from operating mine projects to abandoned mine projects. Currently three projects are operating under the ownership of Arevon Energy (current projects' installed capacity at 14MWe). This case study examines two of those projects

#### *Stillingfleet Mine, Selby Group*

Years of mine operation: 1988 - 2004

Geologic information: Yorkshire Coalfield; Barnsley Seam mined. Average seam thickness of mined coal seam was approximately 3m with a shaft depth of 700m. Generally, geology was difficult with faulting.

Gas emissions: Medium gassy mine. Stillingfleet Mine was interconnected underground to several other mines and therefore the gas reservoir was large.

Mode and volume of gas production: AMM is extracted from the top of the upcast shaft cap. Gas flow extracted in 2019 was around 770Nm<sup>3</sup>/hr at methane concentrations of around 80 to 85% methane. Gas is extracted via positive displacement type lobe blowers at suction vacuum circa 600mbarA. The mine has an excellent gas tight seal allowing a strong vacuum without air ingress.

End use: Gas is used in reciprocating gas engines with 6kV alternators interconnected to the electricity network.

Figure 9.4

**Venting arrangement at the Stillingfleet Mine**



Source: Butler, N., HEL-East Ltd

Figure 9.5

**Stillingfleet Mine gas extraction plant**



Source: Butler, N., HEL-East Ltd

## Harworth Colliery

Years of mine operation: 1923 – 2006

Geological information: Eastern Pennine Basin Coalfield; Top Hard, Blyth, Deep Soft, Haigh Moor and Swallow Wood Seams. Average seam thickness was around 2m, with shaft depth of 850m. Generally, difficult geology with faulting and very gassy coal.

Figure 9.6  
**Harworth Colliery gas engines**



Source: Butler, N., HEL-East Ltd

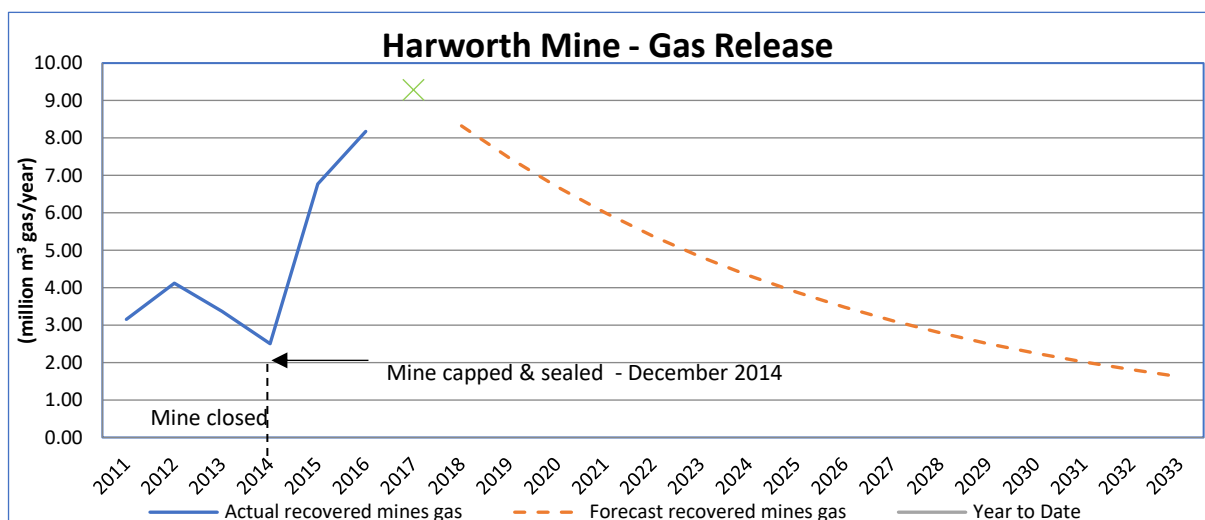
Mode and volume of gas production: AMM is extracted from the top of the downcast shaft cap. Gas flow extracted in 2019 was around 1,080Nm<sup>3</sup>/hr at methane concentrations of around 35% methane. Gas is extracted using liquid ring vacuum pumps at suction vacuum circa 600mbarA. The mine has a cap without perfect sealing, and therefore a limited vacuum can be drawn, which allows some air ingress.

End use: Gas is used in reciprocating gas engines with 415V alternators, transformed up to 11kV interconnected to the electricity network.

Emissions reductions:

Figure 9.7

**Harworth Mine Emissions Forecast**



Source: Robinson, A., Chief Operations Officer, Arevon Energy

### Encouraging policies or incentives for AMM in the UK:

There was a period of incentive for CMM development, which indirectly supported some active mine CMM projects which eventually became AMM projects. However, financial support for AMM power generation in the UK is low, with the only incentive being exemption from the Climate Change Levy Tax.

In 1999, operating gassy coal mines were incentivised by the UK ETS to transition from simple direct venting of methane gas to the atmosphere, to investment in methane utilisation or flaring. As a result, the six projects referred to above were commissioned at operating mines, thus unwittingly establishing infrastructure which after mine closure could be employed for AMM utilisation.

There is no similar ETS incentive for AMM projects, but AMM power projects are exempt from the UK Climate Change Levy (CCL), being effectively treated the same as renewable forms of electricity generation. The CCL is a tax on energy delivered to non-domestic users in the UK. Its aim is to provide an incentive to increase energy efficiency and to reduce GHG emissions. In 2019, this tax was £0.00847/kWh.

When a mine closes, a peak gas emission period occurs for up to a year after mining ceases. This peak gas emission is known as “bonus” gas. If a mine does not have either utilisation in place immediately prior to closure (i.e. already in place during operation) or a plan to install generation immediately after closure, or the mine is sealed tight and gas cannot escape (potentially a dangerous situation), then this valuable bonus gas is lost to the atmosphere for ever. In many cases this first year of bonus gas can pay for the entire plant installation. For this reason, policy incentives are required to encourage AMM development prior to mine closure.

### Lessons learned and conclusions:

When designing an AMM extraction plant, as the gas is extracted from the mine it will tend to be warm and wet, therefore, particularly in the winter, water will condense as soon as it enters the surface pipework. Care should be taken to plan and install suitable water traps and drainage systems to remove water throughout the system to prevent ingress of water to the extraction plant (if appropriate) and to the utilization plant.

Flame arresters should be installed in the system in between the gas extraction points and the utilization plant and in any vent system to prevent any ignition of gas, passing back through the pipework, where there is a flammable air/gas mixture. A flammable air/gas mixture may arise at an abandoned mine, where a utilization plant is being started, or where a leak occurs in the system before the extraction plant (i.e. on the vacuum side). A flammable air/gas mixture may also occur at an abandoned mine site where there is no utilization and barometric fluctuations lead to gas-air mixing underground.

Projects should ideally be planned and initiated before mine closure to take advantage of the miners’ knowledge and the known gas composition and liberation rates at the time of closure. The timing also allows an AMM project developer to utilize and benefit from the mine

surveyor's experience in assessing flooding rates at the mine. Finally, the AMM project developer will be able to benefit from the bonus gas peak immediately after closure.

In general, depending on the resource size and scale, and the number of project opportunities available to the developer, it has proven technically convenient and financially expedient to install multiple containerized gas engine generating packages rather than fixed gas engine installations in buildings. Where over-estimation of AMM gas resources occurs, a fixed infrastructure will lead to much of the investment being unused or underutilized with a low load factor and poor investment return. Conversely, if containerized generators are used, they may be used on other projects, perhaps where another project has under-estimated gas reserves.

Depending on the coal field, we would expect no more than 10 - 20 percent of any group of mines to be suitable for an AMM project. This subset of mines will typically be those mines that a) are gassy, b) had methane drainage during operational mining, and c) are not expected to quickly flood.

Estimation of AMM gas resource can be difficult. The most accurate estimates for projects are developed while mines are still open, as experienced miners can help in planning, and actual gas production can be seen and records analysed. If a mine has been closed for years, then where possible a trial drilling and a test suction well/extraction draw down and recovery test into the mine-workings can be done to assess void space and gas resources. Sophisticated geological modelling software can be used to assess void space and the gas resource for AMM. However, model outputs are dependent on the quality of data input used in the model, and model users should factor uncertainty into the results. In the UK, one developer carried out extensive modelling, generating a reserve equivalent sufficient to generate a 20MW electricity plant. However, after drilling boreholes to intersect the workings, there was only sufficient gas to produce 6MWe. Thus, the need to combine modelling and physical testing is graphically illustrated.

AMM schemes have been operating over more than 20 years in the UK without any major safety incidents or explosions reported arising from AMM utilization.



#### Case Study 4: United States - North Fork Valley, Colorado

The North Fork Valley, located in Delta and Gunnison Counties in western Colorado, has more than a 100-year history of underground coal mining, with two mines beginning operations in 1903, targeting coals of the Somerset Coal Field, which are in the Paonia Shale and Bowie Shale Members of the Lower Cretaceous Mesaverde Formation. Through 2017, just over 323 million tons of coal have been mined in the North Fork Valley. The coal is high-quality bituminous coal with high energy content (~11.6 MJ) and very low contents of ash, sulfur, and mercury, making it ideal for electric power generation as it meets all current US environmental standards. Peak coal production was reached in 2003 from four mines, producing a combined total of 16.5 million short tons, which was 46 percent of the State’s production. In 2013, the valley was home to just three coal mines with active coal leases, West Elk, Bowie, and Elk Creek, producing approximately 10 million tons of coal and employing close to 1,000 people, while emitting 66.5 million cubic meters of methane (949,952 tCO<sub>2</sub>e). In 2017, only the West Elk Mine was operating, producing 4.8 million short tons, or 43.4 percent of the State’s coal production, emitting 26 million cubic meters of methane (441,938 t CO<sub>2</sub>e) from its ventilation and drainage systems. The Bowie Mine is now idled as it has mined out its coal reserves within its current leases’ mine plan. A fire at the Elk Creek mine stopped production and the owner has since begun reclamation.

There are currently at least 14 abandoned mines in the North Fork Valley (**Table 9.2**), with a combined footprint of approximately 5,600 hectares and a total abandoned mine void volume of approximately 91 million cubic meters, based on each mine’s total coal production (**Figure 9.8**). As Bowie closes, followed by West Elk once it mines out its reserves, an additional 131 million cubic meters of abandoned mine void volume will be added to the region.

All of the coal seams exploited in the mines listed in **Table 9.2** are gassy, with several of the larger longwall mines requiring a methane drainage program to supplement the mine’s ventilation system while the mines were active. Therefore, it is safe to say that much of the abandoned mine void space contains methane gas in varying concentrations. In addition, methane has been detected leaking from sealed portals, vent pipes, and abandoned boreholes.

Table 9.2

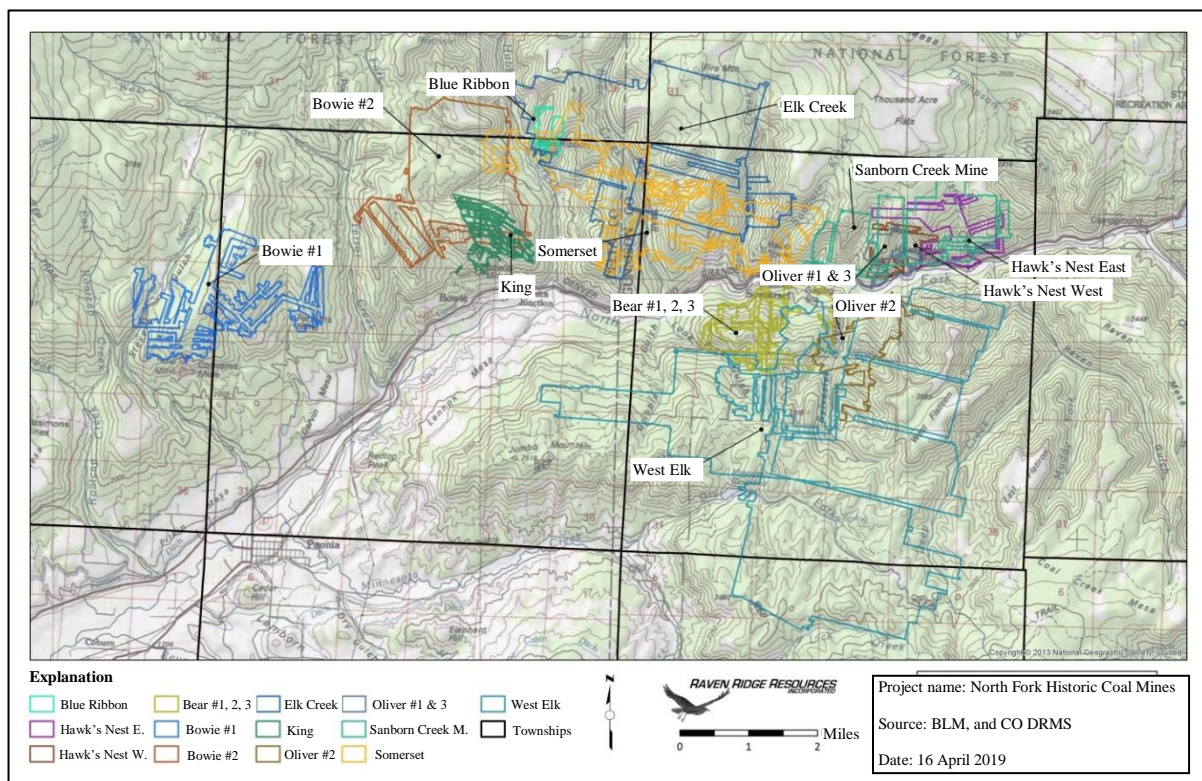
#### Underground Coal Mines of the North Fork Valley

Mine	Status	Years of Operation	Mine Footprint Area (million m <sup>2</sup> )	Mine Footprint Area (hectares)	Total Coal Production (million tons)	Mine Void Volume (million m <sup>3</sup> )	% of total Void (%)
Bear #1, 2, 3	Abandoned	1932 - 1996	6.6	659.6	9.1	6.3	2.8%
Bowie #1	Abandoned	1976 - 1998	4.1	405.9	16.1	11.0	5.0%
Elk Creek	Abandoned	2002 - 2013	17.4	1,736.3	49.4	33.9	15.2%
King	Abandoned	1903 - 1974	1.1	111.3	3.0	2.1	0.9%
Oliver #1 & 3	Abandoned	1923 - 1960	1.0	96.2	1.4	0.9	0.4%
Oliver #2	Abandoned	1945 - 1954	2.4	241.6	0.8	0.5	0.2%

Sanborn Creek	Abandoned	1992 - 2003	6.1	607.6	16.8	11.6	5.2%
Somerset	Abandoned	1903 - 1985	14.3	1,431.9	31.2	21.4	9.6%
Hawk's Nest West	Abandoned	1937 - 1982	1.1	113.2	2.9	2.0	0.9%
Blue Ribbon	Abandoned	1956 - 1963, 1977 - 1984	0.4	36.9	0.6	0.4	0.2%
Hawk's Nest East	Abandoned	1975 - 1982	2.0	203.3	2.0	1.4	0.6%
<b>Total for abandoned mines</b>			<b>56.4</b>	<b>5,643.8</b>	<b>133.2</b>	<b>91.5</b>	
Bowie #2	Idle	1997 - 2016	8.3	825.7	42.6	29.3	13.2%
West Elk	Active	1992 - PRESENT	42.1	4,205.8	148.1	101.7	45.7%
<b>TOTALS</b>			<b>106.7</b>	<b>10,675.2</b>	<b>323.9</b>	<b>222.5</b>	

Source: Marshall, J., 2019, unpublished data compilation and analysis

Figure 9.8  
Map showing active and abandoned mines of the North Fork Valley



Source: Raven Ridge, 2019, unpublished data compilation and analysis

North Fork Energy LLC, a subsidiary of Vessels Coal Gas, operates one abandoned mine methane project at the Elk Creek mine, which was abandoned in 2016, capturing approximately 8,000 cubic meters per day. The project began in 2012 when the mine was active, and to date has destroyed approximately 70 million cubic meters of methane. Vessels, along with other parties, have investigated other options for use of drainage methane at several of the gassy mines in the region, but due to the lack of access to natural gas pipelines,

as well as very low regional electricity sales prices, flaring has been the economically viable method of abatement. However, Vessels was also able to negotiate a 15-year purchase power agreement sell 3 MW of electricity to Holy Cross Energy, a local utility, under Colorado's renewable energy program.

One other flaring project is in the planning stages; Hubbard Creek Coal Gas, LLC, a company based out of southern Florida, is proposing to flare coal mine methane produced from vent holes over the idled Bowie Mine.

The coal leases in the North Fork Valley are all located on Federal land, which means that the U.S. Bureau of Land Management (USBLM) is the regulatory body that oversees exploitation of all natural resources.

Ground-breaking cases in the United States have laid the legal framework for the eventual resolution of issues that arise from attempts to obtain the rights to capture and use CMM and AMM. Two important precedents overshadow the authority and obligations to lease the rights to gas resources that are collocated with coal resources. The first was the landmark case, *AMOCO Production Company v. Southern Ute Tribe* 526 U.S. 865, 875 (1999), in which the US Supreme court ruled that coal leases that were issued under the Coal Lands Acts of 1909 and 1910 do not convey the right to capture and use of natural gas. The Interior Board of Appeals, the appellate review body of the Department of Interior which adjudicates disputes related to the use and disposition of public lands and their resources, ruled that the use of oil and gas leases is not the appropriate mechanism for methane gas capture. In its decision the administrative judges stated that methane gas, such as CMM and AMM, is the inadvertent by-product of coal mining and that it does not constitute a deposit and therefore cannot be leased through normal oil and gas leasing. In an attempt to rectify the issue, the USBLM issued an Instruction Memorandum (IM) 2017-037, which permitted capture and sale of this by-product gas, referenced as waste mine methane (WMM), by amending existing coal leases and incorporating the mechanism into newly issued coal leases. Unfortunately, IM 2017-037 was rescinded by IM 2018-018 out of concern for encumbering coal miners with undue regulations that might adversely impact the economics of coal mining. However, the IM does not state that the USBLM lacks authority and maintains that actions to obtain the right to capture and use these by-product gases are permissible and voluntary.

The Solid Fuels Branch of USBLM oversees the coal estate, which includes the entire life cycle of coal mining, from permitting through release of the coal lease after mining has ceased. Thus, the only mechanism that Solid Fuels Branch can use to approve coal mine methane capture is through the coal lease; yet there is no language in the standard federal coal lease regarding flaring, abatement, or otherwise capturing methane during the coal mining process. Therefore, the coal lessee would have to negotiate a lease addendum or amendment with USBLM. Yet, there remains uncertainty as to how USBLM would regulate methane capture, or how to value the gas from a royalty standpoint.

Once the lessee relinquishes the coal lease and the mine is officially abandoned, there is additional uncertainty as USBLM does not have an official policy for regulating abandoned mine methane. The USBLM Colorado State Director issued a statement that authorization for

a methane capture project at an abandoned coal mine falls under the Liquid Minerals Branch of USBLM, which requires an oil and gas lease. This process requires the project proponent to nominate the parcels for an oil and gas sale, and the USBLM would then conduct a lease sale for the parcel for all potential reservoirs contained in the geologic strata underlying the nominated area. The project proponent would have to be the successful bidder at the sale to acquire the lease. Unfortunately, the Director also suggested that the State of Colorado may be better positioned to regulate abandoned mine methane capture under its various air quality programs.

The lack of clear policies and direction as to how coal mine methane is to be managed has allowed the mining companies to carry on without addressing the issues surrounding their methane emissions, and has been a barrier to further development of this sizable resource.

In 2017 a working group was formed – The North Fork Coal Mine Methane Working Group – with a goal of developing and implementing a comprehensive strategy for education, mitigation and economic utilization of coal mine methane in the North Fork area. Charter members of this group include county commissioners, staff members of mines in the region, Colorado’s US Senators and Representatives, along with representatives of various environmental groups, electric utilities, as well as various relevant Colorado government agencies. Currently, the group is working with the USBLM regional office to encourage the development of official policies that facilitate the use and/or abatement of coal mine methane.

In January 2019, Colorado’s US Senator Bennet and US Representative Neguse introduced the CORE Act, or Colorado Outdoor Recreation and Economic Act (H.R. 823), which includes two sections (Sections 305 and 306) on coal mine methane leasing. This bill calls for development of a pilot program that promotes the capture, beneficial use, mitigation, and/or sequestration of fugitive methane emissions from underground coal mines in the areas of Garfield, Gunnison, Delta, and Pitkin Counties in western Colorado. This bill was presented to Congress on 6 June 2019 and has been considered and marked up, awaiting further action.

### *Case Study 5: United States - Elk Creek Permit Area Abandoned Mine Methane Project*

The Elk Creek Permit Area Abandoned Mine Project (Project) is located in Gunnison County, Colorado, USA. The Elk Creek Mine opened in 2001 and was the largest active underground coal mine in the United States to generate electricity from CMM beginning in 2012. The Project was developed by Vessels Coal Gas (VCG) and is still operated by VCG. The mine was closed and abandoned in February 2016, and the CMM Project transitioned into a multi-mine AMM Project that includes the Elk Creek Mine and four adjacent abandoned mines – Sanborn Creek Mine, Hawks Nest East Mine, Hawks Nest West Mine, and the Somerset Mine. The Sanborn Creek Mine closed in 2003, while the other three mines closed during the 1980s. All of the mines in the group were considered gassy mines when active, especially the Elk Creek and Sanborn Creek mines, daily methane emissions of which averaged 144 and 150 thousand cubic meters per day, respectively.

The project evolved from a unique partnership of companies with different backgrounds. Vessels Coal Gas joined forces with Oxbow Mining (coal mine operator), Holy Cross Electric (utility), and Aspen Skiing Company (end user and financier) to build the \$6 million USD CMM Project in 2012. Wholesale electricity prices are low in the region at \$0.03/kWh, which is typical for U.S. markets, thus the Project needed additional revenues from the environmental attributes to be financially viable.

In addition to selling electricity to a rural electric utility, the Project benefits financially from two separate state policy incentives for which it's eligible – carbon offset credits under the California compliance offset program and renewable energy credits (RECs) approved by Colorado's public utility commission. The carbon offset credits are critical to the economic viability of the Project due to the low electricity prices. From 2016-2018, the Project generated over 500,000 MT CO<sub>2</sub>e in emission reductions (carbon offset), equivalent to removing 36,000 automobiles from U.S. highways. In 2018, carbon offsets were valued at approximately \$13 USD/MTCO<sub>2</sub>e and RECs added about \$0.01/kWh.

High-volatile A and B bituminous coal contained in Upper Cretaceous strata has been mined in the Somerset coalfield since the late 1800s from as many as four coal seams at depths ranging from 150-850 meters. Individual coal seams range from 2-5 meters thick, and total thickness of coal within the area is approximately 13 meters. Coal gas contents are largely a function of overburden depths in the mountainous region with the deeper coals reaching up to 10 m<sup>3</sup>/ton. All the abandoned mine workings from the five mines partially overlay each other creating an AMM zone of influence that can be recovered from two main areas. As a result, methane is recovered from wells located in only two of the mines - Elk Creek (includes mine gas from Somerset) and Sanborn Creek (includes mine gas from Hawks Nest mines).

Since the Elk Creek Mine abandonment, VCG has continued to operate the 3MW power plant in conjunction with an enclosed flaring system recovering approximately 50,000 m<sup>3</sup>/d of methane. AMM is extracted from the underground mine workings and supplied to the methane destruction/end-use technologies via gas blowers that were in place during active mining operations. The Project uses three 1 MW (1500 hp) Guascor lean-burn gas engines to generate electricity and an Abutec flaring system. The electric substation on site interconnects power to the grid at 46 kV where it is then wielded across power transmission

lines to the electric utility and ski area. The Project's reliability for delivering electricity to the grid was high - operational runtime averaged 90-95% annually, both during the active and abandoned mine phases of the Project.

Gas flow meters and a methane analyzer are used to continuously meter the amount of methane destroyed by the Project activities. In addition, engine runtime and flare temperature are continuously monitored to ensure gas destruction and for carbon offset program compliance. All data is collected in a programmable logic controller (PLC) at the site and saved and stored on off-site computers.

The Project is expected to operate through 2026. In 2019-2020, VCG plans to expand the Project into other areas of the abandoned mines not currently contributing to the methane recovery volumes. The capacity of the substation will allow up to 9 MW of electricity to be exported to the grid.

Vessels Coal Gas noted several lessons learned during the Project's development, permitting, and six years of operations.

- Permitting requirements that limit criteria pollutants resulting from combusting CMM (i.e. NO<sub>x</sub>, CO) in end-utilization or destruction equipment need to be considered;
- Education and outreach needed for regulators at all levels to understand CMM and AMM emissions and carbon neutrality of individual projects;
- Must recognize the uncertainty in methane production forecasts and include high-mid-low cases in economic assessments;
- Important to note secondary environmental benefits when presenting Project such as reducing methane emissions as a VOC and ozone precursor as well as a GHG;
- Important to note benefits of reducing short-lived climate pollutants where methane GWP is 86 (20-year) under Assessment Report 5;
- Beneficial to engage local stakeholders and companies during project development.

Figure 9.9

#### **Elk Creek AMM Electric Power Project**



Source: Coté, M., 2016

## Appendices

### Appendix 1 Testing regimes for AMM reservoir characterisation

<i>Reservoir feature</i>	<i>Tests</i>	<i>Results</i>
Water levels and recovery	<ul style="list-style-type: none"> <li>Monitoring of water levels at key point in the underground reservoir. Investigation boreholes may be needed to supplement any existing monitoring facilities</li> <li>Changes to existing de-watering schemes to assess the extent of recovery in all parts of the workings</li> <li>Water quality analysis</li> </ul>	<ul style="list-style-type: none"> <li>Confirmation of water levels, or in some instances confirmation that water has not risen to a specific level</li> <li>Clarification of water recovery rates</li> <li>Indication of extent of transmissivity in the underground workings</li> <li>Consideration of water quality issues and options for discharge</li> </ul>
Open void space	<ul style="list-style-type: none"> <li>Monitoring of passive vents to observe the change in gas pressure, temperature over time</li> </ul>	<ul style="list-style-type: none"> <li>The results can give an indication of the volume of the AMM reservoir but do not take account of gas desorbing from coal seams</li> <li>Rapid pressure fluctuations but low flows may indicate minimal void space and hence a high resistance system or flooding</li> </ul>
Air ingress	<ul style="list-style-type: none"> <li>Active gas pumping tests to monitor oxygen concentration in the extracted gas</li> <li>Use of shallow spike probing around former mine entries to investigate for leakage of mine gas to the surface</li> <li>Smoke tests in the vicinity of mine entries</li> <li>Interaction between monitoring stations to provide an indication of migration routes</li> </ul>	<ul style="list-style-type: none"> <li>Detection of oxygen in the extracted gas indicates air ingress into the AMM reservoir</li> <li>Further tests and review can be undertaken to determine the likely source of leakage</li> <li>Air ingress will dilute the gas and reduce the amount of suction that can be applied to the mine</li> <li>Need to undertake engineering remedial works to former mine entries</li> <li>Potential problems with extraction pipework</li> <li>Results can be used to show the effectiveness of remedial engineering works</li> </ul>
Surface to underground connectivity	<ul style="list-style-type: none"> <li>Measurement of pressure loss between the surface and underground, active pump test may be used to clarify results</li> <li>Active gas pump tests used to confirm the integrity of connections</li> </ul>	<ul style="list-style-type: none"> <li>The resistance of the surface to underground connection can be calculated this value can be confirmed by field tests</li> <li>Excessive pressure loss may indicate a poor underground connection that will hinder gas extraction and may prevent the designed rate being achieved</li> </ul>

Transmissivity underground

- Active pump tests to extract gas from the workings
- Use of monitoring stations located some distance away from the gas extraction point to confirm the extent of suction pressure. The mine fan can be used for this test prior to closure
- Confirmation of transmissivity of the workings. A rapid increase in suction pressure and fall in flow may indicate a partial blockage or minimal void
- Confirmation of the status, and transmissivity of main mine roadways

Gas composition

- Use of portable instruments to monitor gas compositional variations over time. Detection of:
  - Methane
  - Carbon dioxide
  - Oxygen
  - Higher hydrocarbons
  - Hydrogen sulphide
  - Other gases
- Flow measurements
- Pressure measurements
- Monitoring results and gas analysis will provide the calorific value of the gas (not just methane)
- Calorific or heating value is the unit that should be used for financial appraisal
- Identification of potential contaminants that could cause operation/maintenance problems or unacceptable environmental emissions
- Identification of uncontrolled air ingress
- General reservoir characteristics in terms of gas recovery



## *Appendix 2 Key ingredients of an AMM pre-feasibility study*

- A description of the proposed scheme and its location together with a timetable for investigation, development and production with provisional dates for decision stages.
- Results of any gas flow monitoring in the mine before and after closure, the gas drainage history and the date of closure if already abandoned. Valuable information on the potential of a mine to yield gas after closure can be obtained from investigations undertaken while the mine is operational. These include measurements of seam gas contents, gas drainage flows, gas flow in exhausted ventilation air and the extent of main fan influence as an indicator of interconnections to shallow, old workings.
- A preliminary estimate of the gas resource based on the volume of de-stressed coal left in place above the workings and gas content of the coal seams. This will require a representative geological section recording all worked and unworked coal seams. Allowances should be made for water recovery and achievable suction pressures during extraction in arriving at an estimate of the likely recoverable gas volumes (AMM reserves).
- Identification of the number, location and details of recorded mine entries (shafts, inclines, adits and service boreholes).
- Assessment of the possibility of unrecorded mine entries.
- Costs of sealing shafts and drifts to an air-tight standard suitable for AMM extraction; this is fundamentally different from the conventional sealing practice in many developing countries. Consideration should be given to depth to competent ground (rock-head) mine entry sectional area and any existing surface structures, which would require removal. Experience of AMM schemes suggests problems are often associated with air ingress due to inadequate engineering of seals.
- Details of the proposed production testing programme to be undertaken to prove the adequacy of sealing and the gas production rate and quality.
- Engineering measures to be taken underground prior to closure to optimise gas accessibility, e.g., by diverting water flows and installing pipework, using existing pipework, to ensure gas transmission through low areas likely to flood, placing seals in shafts.
- Details of sources and quantities of water flow into the mine and options to control water on closure. This may involve the installation and use of a de-watering scheme the costs of which will have to be borne by the AMM project.
- Identification of any existing surface infrastructure, surface access and costs for site clearance and preparation.
- An assessment of gas utilisation options, existing gas storage and distribution infrastructure, possible industrial and commercial customers and the current local prices for electricity and low to medium heat value gas. The study should also report on the need for and costs associated with any new infrastructure requirements.
- Options to use gas from alternative sources to supplement supply e.g., CMM or natural gas.
- Possible social impact in terms of job creation, job losses and economic stimulation of the area; AMM schemes can be the first re-development project at a closed mine.

- Environmental impacts and benefits through the control of gas emission at the surface and to atmosphere.
- Safety issues.
- Permitting and land access, mineral and gas ownership.
- A preliminary financial appraisal and the estimated cost of a full feasibility study including any civil works and testing programmes.
- Identification of uncertainties and knowledge gaps.
- Proposed investigation and monitoring strategies.

*Appendix 3 Engineering options for the treatment of mine entries on mine closure*

<i>Setting</i>	<i>Issues</i>	<i>Engineering considerations</i>
Shaft cap constructed at rock-head	<ul style="list-style-type: none"> <li>• Depth of cap limited by surface access and need to support excavation at depth to allow access</li> <li>• Working area to allow excavation</li> <li>• Geo-technical properties of cap formation level</li> </ul>	<ul style="list-style-type: none"> <li>• Excavation to allow access to formation level</li> <li>• Cap constructed at rockhead on competent strata no stability issues</li> <li>• Cap keyed into natural strata to form an effective seal, additional sealant can be used to prevent leakage from beneath the cap</li> <li>• Additional low permeability barrier can be constructed around the cap if required</li> </ul>
Shaft cap constructed on shaft liner in deep fill	<ul style="list-style-type: none"> <li>• Geo-technical nature and depth of fill material</li> <li>• Stability of forming the cap on the shaft liner</li> <li>• Access to seal service ducts</li> </ul>	<ul style="list-style-type: none"> <li>• Stability and practicality of forming the cap on the shaft liner and fill material</li> <li>• Limited depth of excavation needed</li> <li>• Need for an additional perimeter barrier around the shaft cap and liner to form an effective seal</li> <li>• Sealing of service ducts</li> </ul>
Shaft treated with grout plug	<ul style="list-style-type: none"> <li>• Geo-technical nature and depth of fill material</li> <li>• Stability of forming the plug</li> <li>• Ability to access service ducts</li> <li>• Depth and thickness of grout plug</li> <li>• Need to have infilled shaft to support formwork for grout plug</li> </ul>	<ul style="list-style-type: none"> <li>• Placement of the grout plug without reducing the permeability of the shaft fill</li> <li>• Installation of pipework through the plug</li> <li>• Need for additional support around the shaft liner to support plug</li> <li>• Options to provide additional protective barrier and seal service ducts</li> </ul>
Drift sealed with a stopping	<ul style="list-style-type: none"> <li>• Depth to rock-head and geo-technical nature of fill material</li> <li>• Method of portal construction</li> <li>• Control of surface water ingress</li> <li>• Access restrictions</li> </ul>	<ul style="list-style-type: none"> <li>• Keying in supporting stopping walls to natural strata to form an effective support and seal</li> <li>• Thickness of stopping and nature of fill material</li> <li>• Need to prevent water accumulating at the stopping wall</li> <li>• Grouting the stopping and surrounding strata</li> <li>• Grading of pipework through the stopping</li> </ul>

*Appendix 4 Equipment and services required for AMM project construction and operation*

<i>Equipment/technologies</i>	<i>Services/activities</i>
Surface drilling – including guided technology and casing while drilling technology for gas production borehole	Determine performance requirements of the scheme
Gas membranes and other products and technologies to effectively seal mine entries	Specification of equipment
Grout injection	Design of civil engineering works, treatment of surface entries, site preparation and construction, installation of AMM plant and associated infrastructure
De-watering pumps, pipework and control systems	Contract preparation
Water treatment	Tender evaluation
Surface gas extraction pumps and control systems	Supervision of site works
Fixed and portable monitoring	Preparation of health and safety plan
Gas collection pipework and control valves	Review of information
Operational and safety monitoring and control systems with remote alarms	Commissioning and problem solving
Gas compression plant	Health and safety policy and plans
Electrical switchgear	Gas sales and power purchase agreements
Remote communication systems	Identification of management structure
Measurement of gas composition (heating value) and flow	Operational procedures
Metering equipment	Emergency (including call out) procedures
Gas treatment and cleaning processes	Audit and review policy
Odour for addition to gas prior to transport for leak detection	Environmental control
Utilisation equipment	Maintenance schedule
	Project management
	Technical support
	Customer liaison
	Business development
	Financial control

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# Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Coal Mines

Coal is central to the energy security of many countries and has played a significant role in alleviating energy poverty around the world. Inevitably, as coal reserves are depleted, or in response to changes in the energy economy, mines are closed and abandoned. Mine closure can provide a small, but significant opportunity to exploit a clean energy resource, Abandoned Mine Methane (AMM), which can be extracted and used with existing technology. The principles outlined herein are not intended to replace or supersede, but to complement existing legal and regulatory frameworks. This publication is meant to provide guidance and support for development of post-mining projects to reduce the overall emissions attributable to the coal mining life cycle by optimising recovery and use of methane that would otherwise be released to atmosphere.

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