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Best Practice Guidance for Effective Management of Coal Mine Methane at National Level:

Monitoring, Reporting, Verification and Mitigation

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Best Practice Guidance for Effective Management of Coal Mine Methane at National Level: Monitoring, Reporting, Verification and Mitigation

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Foreword

The current state of the natural environment is worrisome. According to International Energy Agency outlooks, if annual global greenhouse gas (GHG) emissions continue at today's rates, by 2100 the average temperature on Earth will rise by approximately 2.6°C compared to pre-industrial times. However, emissions of methane (CH_4) have not stabilized and, if they keep growing at the current rates, the planet faces a climate disaster unprecedented in human history - the earth's atmosphere will warm by approximately 4°C by the end of the century. This human-induced change in atmospheric conditions will wreak havoc, imperilling water supplies, food production and potentially causing mass migration and social destabilization.

About a quarter of today's climate change is caused by anthropogenic methane emissions. Methane is an important and potent GHG. Its 100-year global warming potential is 28 times higher than that of carbon dioxide (CO_2). Measured over a 20-year period that factor rises to 84, and on an instantaneous basis to as much as 120. About 60% of global methane emissions are a result of human activity. Eight percent of this powerful climate pollutant comes from coal mines.

Reducing methane emissions is one of the most cost-effective options for limiting the impact of the energy sector on climate. However, it is impossible to design and implement effective methane policies without access to detailed and reliable data on the scale and sources of the emissions. There is an immediate need for national emissions monitoring and reporting schemes that are effective and based on comparable methodologies. Countries that are party to the United Nations Framework Convention on Climate Change (UNFCCC) and are committed to achieving targets set out in the Paris Agreement are subject to a carbon accounting process. Under this framework they are obliged to monitor, collate, and report emissions from all major anthropogenic sources.

In most developed mining countries, emissions from working coal mines are included in domestic inventories. Inventories play an essential role in determining the scale of emissions, planning mitigation policies, and implementing effective actions. Monitoring, reporting and verification (MRV) programmes at local level helps governments not only better understand the local coal mining industry's contribution to the overall methane and other GHG emissions of the country, but also helps to identify the most promising mitigation opportunities. Unfortunately, only a handful of local entities have established such programmes.

UNECE is committed to helping countries to mitigate climate change and it collaborates with other organizations to maximize the effectiveness of its efforts in that field. I am therefore pleased to present this document, developed in partnership with GMI, which is a practical guide for designing national systems to quantify and report methane emissions from coal mines.

Ms. Olga Algayerova
United Nations Under-Secretary-General Executive Secretary
United Nations Economic Commission for Europe

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Sponsoring Organizations

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. The Group of Experts on Coal Mine Methane and Just Transition convenes as a subsidiary body of the Committee, meeting regularly to discuss issues and promote best practices for management, capture and use of the CH_4 gas liberated during the coal mining life cycle (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, CH_4 is the primary component of natural gas and can be converted to usable energy. The reduction of CH_4 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 CH_4 emissions. With respect to coal mine methane, GMI's Coal Subcommittee brings together key experts in coal mine CH_4 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).

Structure

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

The principal authors of this best practice guidance are:
- David Creedy, Sindicatum Sustainable Resources,
- Volha Roshchanka, U.S. Environmental Protection Agency and Co-Chair, Coal Mines Subcommittee, Global Methane Initiative,
- Clark Talkington, Advanced Resources International.

The following individuals contributed their knowledge and experience in writing specific sections on the report:
- Justyna Swolkien, AGH University of Science and Technology, Kraków, Poland
- Brody Wight and Adina Guillespe, GHGSat
- Stefan Möllerherm, Research Center of Post-Mining, Technische Hochschule Georg Agricola, Germany
- Meredydd Evans and Nazar Kholod, Pacific Northwest National Laboratory, United States

Under the direction of the Global Methane Initiative and the UNECE Group of Experts on Coal Mine Methane and Just Transition, editorial review was provided by:

- Denise Mulholland, United States Environmental Protection Agency / Global Methane Initiative
- C. Özgen Karacan, United States Geological Survey
- Raymond C. Pilcher, Raven Ridge Resources, Inc. and Chair, UNECE Group of Experts on Coal Mine Methane and Just Transition
- Michael Coté, Ruby Canyon Environmental, Inc.

UNECE Project Manager:

- Michal Drabik, Secretary, UNECE Group of Experts on Coal Mine Methane and Just Transition

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***Disclaimer*:** The document does not necessarily reflect the position of individual authors, their respective organizations, or the reviewers and partners listed above.

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Acronyms

ACM	Approved Consolidated Methodology
AMM	Abandoned Mine Methane
CARB	California Air Resources Board
CDM	Clean Development Mechanism
CEMS	Continuous Emissions Monitoring System
CERs	Certified Emission Reductions
CH_4	Methane
CBM	Coalbed Methane
CMM	Coal Mine Methane from working underground mines (drained gas and Ventilation Air Methane)
CO_2	Carbon Dioxide
CO_2e	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
IPCC	Intergovernmental Panel on Climate Change
Km	Kilometre
kWh	Kilowatt-hour
m	Metre
m^3/d	Cubic Metres per Day
m^3/m	Cubic Metres per Minute
m^3/t	Cubic Metres of Gas per Metric Tonne of Coal
Mt	Million Tonnes (metric)
MRV	Monitoring, Reporting and Verification
Mtpa	Million Tonnes per Annum
MWe	Megawatt of Electricity Capacity
MWh	Megawatt-hour

QA/QC	Quality Assurance/Quality Control
SMM	Surface mine methane
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
VAM	Ventilation Air Methane
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, 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.

Abandoned coal mine – A mine where the work of all miners has been terminated and production activity and mine ventilation have ceased. Mine shafts might be closed and sealed. For purposes of this document, a coal mine is referred to as “abandoned”, whether or not the mine was closed according to applicable legal requirements. Furthermore, in this document, the terms “abandoned mine” and “closed mine” have the same meaning. The term “abandoned mine” does not mean a mine that has ceased coal production with the intent to restart production or reopen the mine, such as a mine that is temporarily idled.

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.

Coalbed Methane (CBM) – A generic term for the methane-rich gas naturally occurring in coal seams typically comprising 80% to 95% methane (CH_4) with lower proportions of ethane, propane, nitrogen, and carbon dioxide (CO_2). In common international use, this term refers to CH_4 recovered from un-mined coal seams using surface boreholes.

Coal Mine Methane (CMM) – Gas captured at a working coal mine, also referred to as an active coal mine, by underground CH_4 drainage techniques. The gas consists of a mixture of CH_4 and other hydrocarbons and water vapour. It is often diluted with air and associated oxidation products due to unavoidable leakage of air into the gas drainage boreholes or galleries through mining induced fractures and also due to air leakage at imperfect joints in underground pipeline systems. Any gas captured underground, whether drained in advance of or after mining, and any gas drained from surface goaf wells is included in this definition. Pre-mining drained CMM can be of high purity and is considered to be CMM only when the well is mined through.

Closing mine – A mine that is proceeding to closure for any reason with the intent of permanently ceasing all coal production and sealing all mine entries in accordance with applicable legal requirements.

Emission factor – A coefficient that quantifies the emissions or removals of a greenhouse gas per unit of activity. Emission factors are often based on a sample of measured data, averaged to develop a representative rate of emission for a given activity level, under a given set of operating conditions (IPCC, 2006).

Gas drainage – Methods for capturing the naturally occurring gas in coal seams to prevent it entering mine airways. The gas can be removed from coal seams in advance of mining using pre drainage techniques and from coal seams disturbed by the extraction process using post drainage techniques. Often referred to as CH_4 drainage if CH_4 is the main gas component target to be captured. It is also referred to as mine degasification.

Longwall mining – A type of underground mining method where coal is extracted mechanically from a coalface typically around 250-450m in length. The coalface is generally equipped with a machine, known as a "shearer", that cuts the coal and loads it onto an armoured face conveyor (AFC) that runs the length of the coalface. The face is accessed by two parallel roadways that are used for transporting produced coal away from the face as well as materials, services and ventilation. After each pass of the shearer, the face supports are advanced and the strata behind the coalface is allowed to collapse. The method mines coal as a rectangular panel of certain length and coalface dimensions.

Methane leaks – The unplanned release of CH_4 from plant, production operations, systems and processes, typically from flanges, joints and connections. In certain cases, leaks may occur from cracks and fractures on the ground surface too.

Methane measurement – The process of taking a reading of the CH_4 concentration or CH_4 emission, or flow rate at a specific point in time. If CH_4 is mixed with air, typical units for concentration measurement would be parts per million (ppm), parts per billion (ppb) or percent, and the mass flow rate can be measured as kilograms per hour (kg/h). Note that it is important to understand global and local background CH_4 concentrations to contextualize the data. Emissions measurements may be performed as one-time activities, at regular intervals or on a continuous basis, but it is important that the measurements are representative of typical emissions.

Room-and-pillar mining – A type of mining in which coal is extracted from short faces, leaving pillars of ground support in place, thus forming an interconnected matrix of rooms and pillars. In some instances, pillars are progressively removed, and the roof is allowed to cave to increase the recovery efficiency.

Specific emission – Specific emissions of CH_4 is measured in cubic metres (m^3) of CH_4 emitted per tonne of coal mined and is denoted as m^3/t. Specific emissions may also be referred to as relative emissions.

Surface Mine Methane (SMM) – Methane contained in coal and surrounding strata that is released as a result of surface mining operations.

Tier (IPCC GHG Guidelines) – A tier represents a level of methodological complexity. Usually, three tiers are provided. Tier 1 is the basic method, Tier 2 – intermediate, and Tier 3 – most demanding in terms of complexity and data requirements. Tiers 2 and 3 are sometimes referred to as higher-tier methods and are generally considered to be more accurate than Tier 1.

Ventilation Air Methane (VAM) – Methane emitted from coal seams, and other gas-bearing strata, that enters the ventilation air and is exhausted from the ventilation shaft at a low concentration, typically in the range of 0.1% to 1.0% by volume.

Executive summary

Methane (CH_4) is the second most prevalent anthropogenic greenhouse gas (GHG) after carbon dioxide (CO_2), with a Global Warming Potential (GWP) 28-34 times more potent than CO_2 over a 100-year timeframe. Coal mining, a major source of CH_4 emissions, accounts for about 12% of global anthropogenic CH_4 emissions (U.S. EPA, 2019). Most emissions come from underground coal mines, predominantly working mines, but emissions from abandoned underground mines are increasing. National monitoring, reporting and verification (MRV) programmes not only help countries better understand the contribution of coal mining to their overall CH_4 and GHG emissions, but also identify opportunities for mitigation, ranging from identifying prospective locations for coal mine methane (CMM), abandoned mine methane (AMM) and surface mine methane (SMM) mitigation projects to informing the design of policies for CMM, AMM and SMM.

Designing effective MRV programmes for the coal sector requires understanding concepts about coal geology and coal mining. Coal seams hold different amounts of CH_4 depending on coal rank (i.e., measure of coal maturity) and geological history. Higher rank coals tend to have higher CH_4 contents. The disturbance of coal and intervening strata by mining leads to release of CH_4 from coal seams and any associated gas bearing strata. As mining progresses over a coalfield, changes in geology, seam gas content, mining rate and interactions between workings in different seams lead to variability in CH_4 flows. Understanding the CH_4 flow variability and its underlying reasons is essential when designing measurement and verification requirements of MRV programmes.

Other important factors that can impact CMM, AMM and SMM emissions are the types of mines and how CH_4 is released from the mined seams and adjacent strata. Mines are generally characterised as working underground mines, abandoned underground mines, or surface mines. Working underground mines are believed to emit 90% of global CMM emissions, of which about 60-80% is emitted in very dilute form (typically less than 1% CH_4) through the mine ventilation air and the remainder is emitted through gas drainage systems. All underground mines have ventilation systems, but gas drainage systems are only used in a subset of underground mines where ventilation systems are insufficient on their own to manage CH_4 emissions. Notably, CH_4 concentrations and flow volumes can vary considerably based on geologic and operational conditions. This has implications for mine safety, CH_4 emissions and mitigation potential.

When a mine is abandoned, all services are severed, including ventilation. Methane production and emissions do not stop at the cessation of mining, and CH_4 continues to desorb from the strata disturbed by coal extraction. Initial emissions can be high at closed underground mines before decreasing over time. Hydrogeologic conditions and whether the mine is flooded with groundwater after closure will also affect the rate of CH_4 desorption and the volume of emissions.

Surface mines will release CH_4 from coal and other gas-bearing strata disturbed through excavation. Significant CH_4 emissions at individual surface mines are rare and can be difficult to capture, although there are a limited number of instances of gas capture from surface coal seams prior to excavation.

Action to reduce CH_4 emissions requires a good understanding of emission sources at national, subnational and local levels. Only with reliable emissions data, can policymakers design effective GHG policies, evaluate mitigation opportunities, and comply with their international climate commitments. MRV can provide governments, industry and the public with a more accurate assessment of CMM, AMM and SMM emissions, emission reductions, and mitigation potential.

National inventories quantify emissions that occur during mining as well as from post-mining activities of processing, storage and transportation. MRV programmes support collection of robust data that can help determine the full scale of CH_4 emissions from a nation's coal mines, target and capture the mitigation potential from coal mining, as well as support mitigation through appropriate policies. MRV can help assess and track the effectiveness of climate policy decisions, such as, at reducing barriers to project development. MRV also facilitates tracking of mitigation action and impact. The link between MRV and mitigation is especially important. Policies have been introduced in some countries to encourage investment in CMM, AMM and SMM mitigation projects but, in many instances, because they have not been informed by robust data, they have not been sufficiently effective to achieve the necessary degree of mitigation.

The three elements of MRV are often differentiated, but each element is complementary to and dependent on the other two. *Monitoring* includes the measurement of emissions data, but there are many different options for monitoring emissions with varying degrees of accuracy. Methods employed thus far include the use of emission factors, spot measurement using handheld instruments, and continuous emissions monitoring systems (CEMS). MRV systems are considered most robust if they are compiled with measured, facility-level data as much as practically possible. Data collection with higher frequencies, or higher sampling rates, is generally acknowledged to provide greater accuracy as such data can detect variations due to diurnal temperature or pressure changes and changes due to operational factors while handling statistical variations around the mean and sampling errors. Such an approach to estimating CH_4 emissions is termed "bottom-up". Still, even the most thorough and detailed monitoring methods require skilled and trained staff, properly calibrated and maintained equipment installed at the most relevant and important locations, appropriate monitoring frequencies and accurate interpretation of results based on measurement locations.

The reported data are likely to be cumbersome and possibly incomprehensible to most users in their raw state. Therefore, an effective *Reporting* system facilitates accurate and expeditious reporting and distillation of the data into formats that can be understood by reporting facilities and users of the data. The reporting system allows stakeholders, including the emitting facilities, to track changes in emissions and emission reductions over time. Users may also gain insight into operating or commercial conditions that can impact emissions at individual facilities or in the broader mining industry. Good practice is to report as much detail as reasonably possible.

Verification is the final and necessary step to ensure the veracity of reported data as well as its consistency and compliance with reporting requirements. It is particularly important to provide decisionmakers with the confidence to formulate policies based on the data and, especially, to facilitate public acceptance of the data. Verification can take many forms but generally entails review and confirmation of the data by the party receiving the data, e.g. by a government agency, or by an independent third party. The level of verification depends largely on available resources and the purpose of verification and could include remote sensing, such as aerial or satellite surveys, in addition to document reviews or site visits.

Recognizing the significant contribution of the coal industry to the global CH_4 emissions budget and the critical importance of effective MRV in quantifying emissions and facilitating CH_4 mitigation, this document aims to offer practical considerations for designing national systems that methodologically quantify and accurately report CH_4 emissions from coal mines. The focus of this document is monitoring, reporting and verifying emissions from working and abandoned mines, and it applies to both underground and surface coal mines. More attention is given to underground mines because they are believed to be a larger emission source due to their depth, generally higher gas contents and higher rates of multi-seam disturbance in high production longwalls. Underground mines are also more conducive to mitigation. Additionally, more practical experience exists with monitoring and mitigating CH_4 from underground coal mines.

Decisionmakers must consider a range of factors to determine the most appropriate and effective MRV design for a particular jurisdiction, including policy priorities, economic impacts, cultural impacts, logistics and other factors. Existing experience from MRV programmes around the world shows that the most important considerations include:

- Aligning the MRV programme with the existing policy framework, such as legislative, regulatory or administrative approaches
- Clarifying the roles for relevant stakeholders
- Understanding the nature and sources of coal sector emissions and options for monitoring emissions from those sources
- Establishing standards for monitoring and verification of measurements at the facility level
- Determining target subsectors within the coal sector: working, abandoned or surface mines
- Choosing reporting thresholds (by facility type, emission size, facility size or other options)
- Defining programme structure and administration (reporting frequency, platform, record keeping, publication).

Ultimately, the design of the programme depends on the many predetermined country-specific factors, such as the governance system, policy objectives, capacity of government agencies and, importantly, budgets. Ideally, the MRV system should be robust enough to provide reliable data to foster utilisation of CH_4 and realise emission reductions from the coal sector. Proper accounting of CMM, AMM and SMM identifies targets for immediate and effective action on emissions worldwide.

1. Introduction

Key messages

- Significant CH_4 emissions arise from coal mines globally that, with suitable policy support, present opportunities for enhancing climate change mitigation during energy transition.
- Quantifying current emissions and the impact of mitigation, through MRV programmes, is essential for policy makers in designing and assessing the effectiveness of action programmes.
- Measurement remains unsurpassed in quantifying emissions as it can deliver more accurate, detailed national emission estimates than empirical methods.

Methane (CH_4) is the second most prevalent anthropogenic greenhouse gas (GHG) after carbon dioxide (CO_2). Each molecule of CH_4 is about 28-34 times more potent than CO_2 in its warming capacity, or Global Warming Potential (GWP), over a 100-year timeframe (IPCC, 2014)[1]. Human activity has caused concentrations of CH_4 in the atmosphere to more than double, reaching about 1,800 parts per billion, compared with the concentrations that were present around 1750, before the Industrial Revolution began (IPCC, 2014). Recent atmospheric measurements by the United States National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory showed that in 2020, CO_2 emissions were lower than they could have been because of the economic slowdown caused by the COVID-19 pandemic, yet the amount of CH_4 in the atmosphere jumped to record levels in that year, representing the largest annual increase recorded (NOAA, 2021). Given that CH_4 is a very powerful greenhouse gas, responsible for about 30% of warming since pre-industrial times, reductions of CH_4 emissions are needed from all sectors of the global economy to avoid catastrophic effects on natural and human systems.

A recent United Nations Environment Programme (UNEP) report reiterates that achieving climate benefits in the first half of the century is impossible without addressing CH_4 emissions, while CO_2 emission reductions are key to long-term climate stabilisation (UNEP/Climate and Clean Air Coalition (CCAC), 2021). Methane's short atmospheric lifetime means acting now can quickly reduce human impact on climate in the near term. Without reductions in the near future, rapid changes to Earth's climate over the next few decades will limit the ability of human and natural systems to adapt (UNEP/CCAC, 2021). This is especially problematic for poor and marginalised communities, which are more vulnerable to climate change.

[1] The 100-year GWP is based on the energy absorbed by a gas over 100 years. An alternative metric is to consider the impact of gases over 20 years and measure how much energy they absorb over 20 years, or 20-year GWP. For CH_4, which has a short lifetime, the 20-year GWP of 84–87 is much greater than the 100-year GWP.

Methane also harms human and ecosystem health by contributing to the formation of ground-level ozone. Reducing emissions of CH_4 simultaneously reduces climate risks and lowers ground-level ozone pollution. Every million tonnes of CH_4 reduced helps lower hospitalization due to asthma attacks, premature deaths from respiratory and cardiovascular disease as well as avoid loss of economic productivity and yield of important agricultural crops (UNEP/CCAC, 2021).

World leaders called for action on CH_4 ahead of the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow, UK, that took place in November 2021. IEA's recent analysis of the stated polices and commitments shows that the world has so far fallen short of shared sustainability goals, including to keep global warming to 1.5°Celsius, beyond which humans will experience the most severe impacts of extreme weather, rising seas and crop failures (IEA, 2021). The urgency of addressing climate change requires ambition from policymakers, industry and private individuals. Methane reductions are some of the easiest and most cost-effective to achieve.

Monitoring, reporting and verifying (MRV) emissions, including CH_4 from coal mining, is an important component to delivering on international climate commitments in the context of the Paris Agreement. As countries develop their nationally determined contributions (NDCs), Article 13 of the Paris Agreement calls for "an enhanced transparency framework for action and support". Such a framework is imperative to assessing countries' efforts as well as collective achievements towards the global climate mitigation goals.

What is MRV

Monitoring, Reporting and Verification (MRV) is a term used to describe measures taken by countries and facilities to collect and confirm data on the production and mitigation of emissions. The three components are distinct but interrelated.

Monitoring means direct measurement or estimated calculations of emission and emission reductions following strict guidance and protocols, such as the IPCC Guidelines and methodologies or protocols approved for use in regulatory or voluntary programmes. This can include direct measurement using devices or estimation using simple methods or complex models.

Reporting means documentation intended to inform all interested parties. This includes information on methodologies, assumptions and data. Reporting protocols often vary by jurisdiction and may require very detailed reports to substantiate all reported emissions data or less detailed summaries with the most relevant data reported.

Verification means specific procedures or expert reviews used to verify the suitability of the adopted methodology, quality of the data and estimates. Verification can be internal or external.

Source: adapted from UNECE (2019), Best Practice Guidance for Effective Methane Management in the Oil and Gas Sector: Monitoring, Reporting and Verification (MRV) and Mitigation, ECE Energy Series No. 65 and ECE/ENERGY/129.
https://unece.org/sustainable-energymethane-management/best-practice-guidance-effective-methane-management-oil-and

Many national level inventories are not sufficiently detailed, source-specific, or are reliable enough to effectively inform policies or target and prioritize mitigation opportunities and actions. Action on CH_4 requires solid understanding of emission sources at national, subnational and local levels. Only with reliable emissions data can policymakers design effective GHG policies, evaluate mitigation opportunities, and comply with their international climate commitments.

A consistent, reliable, transparent and verifiable approach to MRV will contribute to improved inventory accuracy and more effective decision making at local, national, and international levels. This document aims to offer practical considerations for designing national systems for systematically quantifying and accurately reporting CH_4 emissions from coal mines. It covers monitoring, reporting and verifying of emissions at the national level from working and abandoned mines and can be applied to both underground and surface coal mines. More attention is given to underground mines since they are believed to be a larger contributor to CH_4 emissions due to their generally higher gas content and multi-seam disturbance, and because more practical experience exists with monitoring and mitigating CH_4 from underground mines. Project-level measurement, reporting and verification are important in forming the basis of carbon markets but are only briefly covered here to explore the overlap between national and project-level MRVs.

1.1 Global coal mine methane emissions and information sources

Global estimates can paint a broad picture of coal mine methane (CMM), abandoned mine methane (AMM) and surface mine methane (SMM) emissions and emission sources. Coal mines account for about 12% of global anthropogenic CH_4 emissions globally (U.S. EPA, 2019), most of which come from underground mines. Data for 2015 shows that in China, coal mining-related CH_4 emissions account for 46% of the country's total anthropogenic CH_4, while in India, CMM, AMM and SMM emissions account for 4% of CH_4 emissions; in Australia - 26%; in Russia - 7%; in Kazakhstan - 41% and in Poland - 35% (U.S. EPA, 2019). Such information can be useful in understanding the broader set of mitigation options in coal producing countries (see **Table 1.1**).

Table 1.1
Top 10 hard coal producing countries in 2019

Country	Hard Coal Production (kt)
China	3,469,817
India	718,625
Australia	433,601
Russia	335,721
United States	312,522
South Africa	253,569
Kazakhstan	98,976
Indonesia	96,924
Colombia	82,065
Poland	61,623

Source: IEA, 2021

Global data on CMM, AMM and SMM emissions come from several international estimates, including those conducted by U.S. EPA, the Emissions Database for Global Atmospheric Research (EDGAR), and the International Energy Agency (IEA) (U.S. EPA, 2020; EC Joint Research Center, 2020; IEA, 2020). These estimates rely largely on national submissions to United Nations Framework Convention on Climate Change (UNFCCC) (see **Table 1.2**), which has historically had different reporting requirements for Annex I and non-Annex I countries in terms of submission frequency and methodological approaches.

All signatories to the UNFCCC prepare annual inventories of greenhouse gas emissions and sinks. The Intergovernmental Panel on Climate Change (IPCC) has established three tiers of inventory methodologies from the more general Tier 1 using general emissions factors to Tier 2 using national- or basin-specific emission factors to the detailed Tier 3 based on site-specific measurements (bottom-up). **Table 1.2** identifies the most recent submissions for coal sector emissions from the top 5 coal producing countries as well as the methodology tiers used for reporting the CMM, AMM and SMM data (as stated by the submitting country, which might not always align with IPCC's definition of the methodology).

Table 1.2

Reporting of national CH_4 emissions inventory data to the UNFCCC by coal producing countries†

Country	Year of the Latest Coal Mine CH_4 Data	Latest Submission	Tier Used (as Stated in the Country Submission)
China	2010 2014	2019 – NC3 2019 – BUR2	Underground coal mines: Tier 2 method; surface coal mining: Tier 1 method; post-mining activities: Tier 2 method; abandoned coal mines: Tier 1 method in 2006 IPCC Guidelines
India	2000 2016	2012 – NC2 2021 – BUR3	Tier 2 and Tier 3
Australia	2019	2021 – NIR*	Tier 2 and Tier 3
Russia	2019	2021 – NIR*	Tier 2, except for post-mining activities from surface mines, which are Tier 1; abandoned mines assumed not to be a source of emissions
United States	2019	2021 – NIR*	Underground coal mines: Tier 3 method; surface coal mining: Tier 2 method; post-mining activities: Tier 2 method; abandoned coal mines: Tier 2 method

Note:

(†) as of the date of this publication.

(*) NIR: National Inventory Report, annual by Annex 1 Parties, NC: National Communications by non-Annex 1 Parties (NC3 means third submission), BUR: Biennial Update Report by non-Annex 1 Parties.

Sources: UNFCCC, https://unfccc.int/non-annex-I-NCs; https://unfccc.int/BURs; https://unfccc.int/ghg-inventories-annex-i-parties/2020

Global approaches described above represent annual (at best) assessments of emissions at national scales. These assessments aggregate emissions from multiple sources or can rely on calculations based on limited measurements, combining emission factors and activity data/equipment count. Global or national estimates can also be based on measured concentrations or remote sensing of emitted gases in the atmosphere, as have been described in multiple studies (Barkley et al., 2019; Miller et al., 2019), although approaches using remote sensing have not been widely used by policymakers or in official reporting of national GHG emissions for coal mines.

To design effective policies and programmes, policymakers need reliable, quantitative information on their CH_4 emission sources. Similarly, companies need accurate, measured data at the facility level to assess their mitigation options, implement mitigation activities, reduce their capital and operating costs, and ensure safe operations. Combining an understanding of geological concept and mining practices with principles of emission quantification provide confidence in the reported data and can help policymakers design sound MRV programmes for the coal sector that will reliably quantify emissions at national and company levels. Such quantification also helps assess emission reduction potential and the progress of emission reduction efforts.

1.2 Bottom-up national MRV

Unlike global estimates and country inventories submitted to UNFCCC, national MRV systems are considered most robust if they are compiled with measured, facility-level data as much as practically possible (also defined as an IPCC Tier 3 approach). National MRVs that rely on measured facility-level data can be considered to have lower uncertainty, better spatial resolution, more disaggregated inventory categories, as well as have the potential to offer improved overall quality and accuracy of the inventory (IPCC, 2011). Such an approach for estimating CH_4 emissions, termed "bottom-up", is most closely linked to mitigation, because mitigation occurs at the facility level. Facility-level data can capture the nuances of CH_4 emissions and emission reductions that are obtained through mitigation at different locations. In addition to measurements, the bottom-up approach to MRV can involve modelling of individual sources and calculation using emission factors, activity data, and process-based models, where necessary. Modelling and calculation can be improved with more data and information available; however, measurement of emissions at facilities remains unsurpassed, as it can help obtain more accurate, detailed national emission estimates, which, in turn, can help facilities and policymakers design policies and assess mitigation opportunities.

When monitoring emissions through measurement, it is important to consider the temporal and spatial scales of measurements, particularly, in relation to the variability of CH_4 flow and concentration at sources. Another critical aspect of obtaining measurement data is adoption of standards for and ensuring calibration of measurement equipment as well as its good working order. Chapter 2 explores the variability of CH_4 flow and concentration at coal mines and the peculiarities of emissions from working and abandoned coal mines, as well as surface and underground mines, which includes ventilation and drainage emissions.

Reporting of monitored emissions would ideally occur through a reporting system that is user-friendly for facilities to report into, while capable of generating outputs with verified data that are easy to understand for all stakeholders. Chapter 5 includes descriptions of reporting systems in the examples of existing national MRV frameworks.

Verification can happen at different levels of aggregation using methods described in Chapter 3. In addition, remote sensing and aerial measurements offer promising ways to verify existing data, and more research can help ensure that these technologies are adapted and widely used for verification of verification.

Finally, one important aspect of CH_4 MRV in the coal sector is that similar or related data might be collected by different regulatory authorities at the same time, whether for safety, tax or ownership considerations. Policymakers should consider the data collection burden on facilities comprehensively and ensure that coordination mechanisms are in place among government agencies collecting any data from coal mines. Coal mines might already be collecting data on CH_4 flow rates and concentrations for safety reasons, and opportunities exist to use these data for inventory reporting and mitigation.

1.3 MRV and mitigation

Mitigation is often the eventual goal for MRV programmes, and MRV programmes that rely on facility-level data are most suited to support mitigation. Facility-level MRV data can also help ensure that mitigation is most cost-effective by highlighting specific opportunities for mitigation and providing data to potential project developers.

MRV and mitigation practices at the mine and company level interconnect with those developed at national level. This is especially true where bottom-up measurements contribute to the national inventory. For example, in the United States, the GHG inventory relies on measured data for ventilation emissions, gas drainage system emissions, and emission reductions taken at the gassiest underground mines and reported for compliance with the United States Greenhouse Gas Reporting Program (see **Figure 1.1**). For non-reporting mines, the United States inventory relies on measured ventilation data taken by the United States Mine Safety & Health Administration (MSHA). Australia also relies on measured and reported CMM, AMM and SMM data for its GHG inventory. National practices can also be influenced by international guidelines and commitments, such as those established under the IPCC and the UNFCCC, especially Tier 3 methodologies, but also Tier 2 methodologies in some cases.

Figure 1.1

Portal used by reporting coal mining facilities in the United States to enter measured data for ventilation emissions, gas drainage system emissions and emission reductions

The portal, available at https://ghgreporting.epa.gov, is maintained by U.S. Environmental Protection Agency in compliance with requirements of the Greenhouse Gas Reporting Program.

MRV is important for policy design as reliable quantification of emissions is essential for monitoring compliance and assessing progress of emission reduction efforts. In addition, MRV data can be used to facilitate the design of voluntary outreach or capacity building programmes that reduce informational, institutional or other barriers for mitigation action. Examples of such programmes are the Global Methane Initiative (GMI), Coalbed Methane Outreach Program (CMOP), managed by United States Environmental Protection Agency, the China Coal Information Institute, the India Coalbed Methane Clearinghouse, and the International Centres of Excellence (ICE) on Coal Mine Methane in Poland and China.

Figure 1.2

A CMM production well pad at a working underground coal mine in Alabama, United States

Source: United States Environmental Protection Agency

Accurate accounting of CH_4 emissions from the mining sector, therefore, underpins robust GHG inventories while supporting public policy and industry objectives to reduce emissions, improves mine safety, and identifies where mitigation policies need to be strengthened to achieve national GHG emission reduction objectives. Policies have been introduced in some countries to reduce barriers and encourage investment in CH_4 mitigation projects at coal mines but, in many instances, introduced policies have fallen short of achieving the necessary degree of mitigation, and many cost-effective reductions remain unmitigated.

2. Sources of coal mine methane emissions

Key messages

- It is important to recognise the inherent variability of CH_4 concentrations and flows in the design of monitoring systems.
- Emissions of CH_4 at coal mines are an inevitable consequence of coal extraction. Assuming other conditions remain the same, the faster the coal is extracted, the higher the emission rate.
- The volumes of CH_4 emitted during extraction depend on the geology of the deposit and the coal extraction method.
- When mining ceases gas continues to be emitted and therefore abandoned underground mines can be significant emission sources.

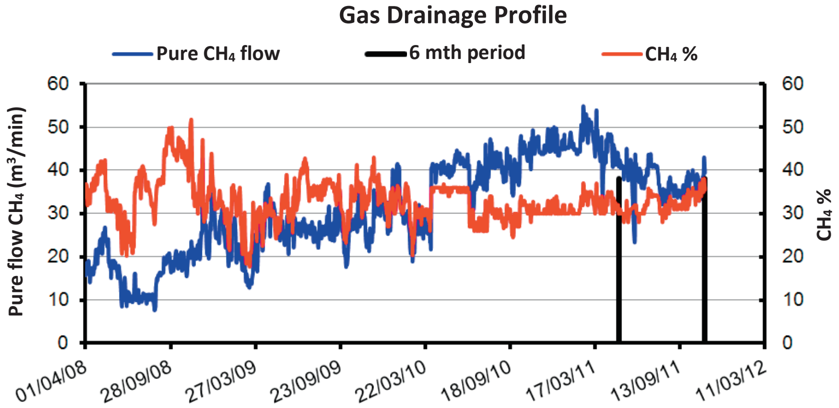
2.1 Variability in methane flows

When designing an emission monitoring and reporting programme, it is important to understand that inherent variability of CH_4 concentrations and flows. As mining progresses in a coalfield, changes in geology, seam gas content, mining rate and interactions between workings in different seams lead to variability in CH_4 flows and concentrations. Variability in flows and concentration is also impacted by leakages through fractured strata and in pipeline systems. Examples of the variability of CH_4 concentrations in drained gas and ventilation air are illustrated in **Figures 2.1 & 2.2**.

Coal seams hold different amounts of gas depending on coal rank (i.e., maturity) and geological history. With a few exceptions, CH_4 is the main gas present in coal seams. Methane contents of coal can vary from less than $1m^3/t$ (cubic metres of gas per tonne of coal) to over $20m^3/t$. Higher rank coals tend to have higher gas contents but there are exceptions where gas loss has occurred as a result of geological events. The disturbance of coal and intervening strata by mining leads to release of gas from coal seams and any associated gas-bearing strata. The greater the volume of coal and gas bearing strata disturbed per unit of time, the higher the emissions. That is, the gas emission rate is largely proportional to the coal production rate, if everything else remains constant. For instance, if the coal seams in the roof strata become thinner, or the coal rank reduces, or the roof does not collapse fully due to a strong bridging layer, emission rate may decrease. Stops and starts in production cause changes in the gas emission rate, the detail of which can be observed in high frequency monitoring data.

Figure 2.1

Flow variability in a mine gas drainage system

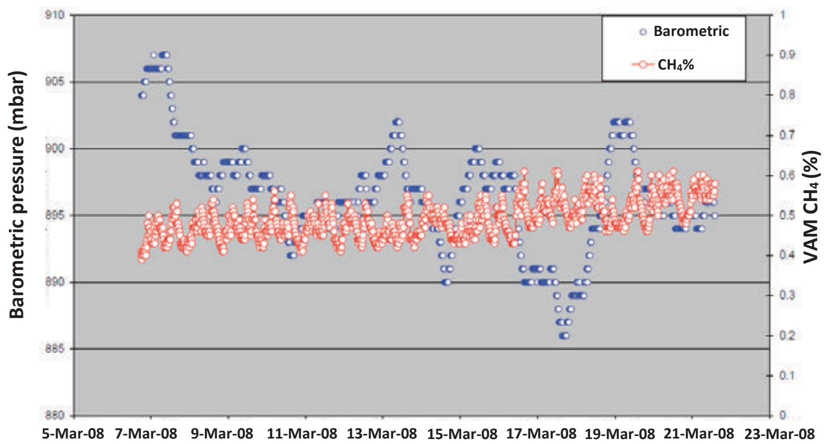


Source: Sindicatum Sustainable Resources

The higher the gas contents of the seams, the higher the emissions of a mine tend to be. In general, underground longwall mines emit more gas than any other type of mine because longwall mining associated caving of strata disturbs not only the worked seam but can also de-stress coal seams and other gas-bearing strata up to 150m in the roof strata and down to 50m in the floor, all of which contribute gas. This interval is called the gas emission zone of the longwall. The actual vertical extent of de-stressing, and thus the size of the gas emission zone, depends on the longwall panel dimensions, depth of the mine and on the strata properties (UNECE, 2016). When mining ceases, gas continues to be emitted at a decreasing rate. However, some room-and-pillar mines, despite their minimal strata disturbance, are known to be gassy, even after closure, presumably due to high strata gas contents and natural permeability. Mined coal also continues to emit gas during handling, processing, transport and storage; these emissions are collectively grouped as "post-mining emissions" in national inventories.

Figure 2.2

Variability of CH_4 concentration in a mine ventilation shaft



Source: Sindicatum Sustainable Resources

For reporting purposes, coal mining-related CH_4 emissions are generally classified as emissions from:

- Working underground mines (CMM, consisting of drained CH_4 and VAM)
- Abandoned (underground) mines (AMM)
- Surface mines (SMM)
- Post-mining (emissions from coal after leaving the mine, such as processing, storage, transportation).

2.2 Working underground mines

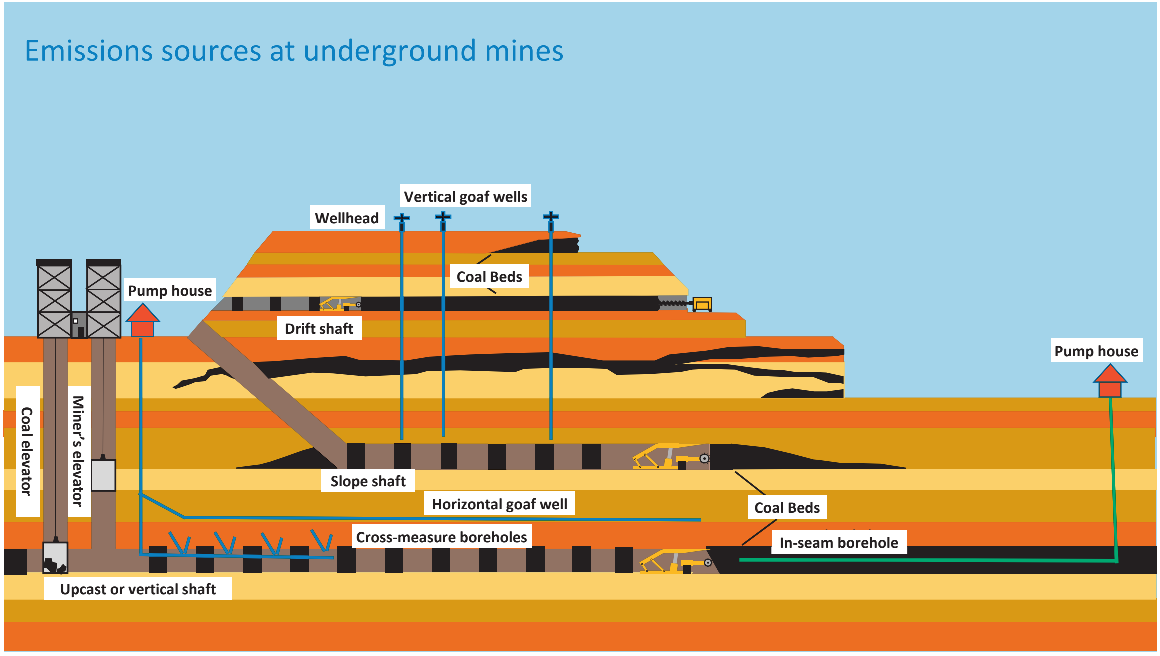
Although uncertainties exist, working underground mines are believed to emit 90% of global CH_4 emissions from coal mines, of which about 60-80% is emitted in very dilute form (typically less than 1% CH_4) through the mine ventilation air (UNECE, 2016). There are two main methods of underground coal extraction, namely longwall and room-and-pillar, although both have many variants. Longwall mines account for the predominant share of CMM emissions from underground mining. Room-and-pillar mines are less gassy than longwall mines in the same geological setting because they disturb less strata per tonne of coal mined. Where the pillars are removed as a final phase of mining, additional gas release can occur due to the increased strata disturbance as the pillars supporting the roof are removed to allow caving.

Methane control systems in mines are designed to prevent, wherever possible, the occurrence of gas-air mixtures in the explosive range of 5-15%. Ventilation provides the primary control system for removing CH_4 from underground workings for safety reasons. Sufficient air must be provided to ensure that in working areas of the mine, CH_4 can be diluted below maximum permissible limits, typically in the range 1% to 2% depending on country and practice. Fresh air is drawn into the mine, passed around the working areas picking up CH_4 and exhausted at an “upcast” shaft (a vertical mine entry) or drift (an inclined mine entry). Even at low concentrations, however, the large volumes of air exhausted at ventilation shafts, which can be in excess of 500 m^3/s, result in very large CH_4 emissions from mine ventilation shafts. In the United States, for example, several large underground mines have reported ventilation emissions at or approaching 100,000 t CH_4 per year to the U.S. Environmental Protection Agency’s Greenhouse Gas Reporting Program (U.S. EPA, 2019).

Where ventilation alone is insufficient to dilute CH_4 concentrations to comply with statutory limits, gas drainage systems are used to intercept gas before it can enter the mine workings. There are two approaches to gas drainage. The first is extraction of gas through boreholes drilled into coal seams before mining starts known as pre-mine drainage, and the second is drainage of gas from strata disturbed by mining, known as post-mine drainage. The former can produce high quality gas suitable for utilisation, whereas post-mine drained gas (**Figure 2.1**) can be of variable quality and careful management is needed to minimise dilution by air to avoid the formation of potentially explosive mixtures in pipelines. The drained gas is either used or, in some instances, flared or vented to the atmosphere. The emissions from different locations of working underground mines are, therefore, manifested as point sources, namely, shafts exhausting mine ventilation air, vents for unused drained CH_4 and any venting boreholes installed in sealed areas, all of which can be readily measured. In some countries, post-mine drainage boreholes are drilled from the surface and the methane vented directly to the atmosphere or used as fuel for the gas extraction pumps. In some instances, the surplus gas is flared to mitigate emissions. These are also point sources requiring monitoring at each borehole rather than at a central gas collection station. Where gas quality and quantities are sufficient, the gas may be gathered in pipelines for utilisation.

Figure 2.3

Point sources of CH_4 emission in an underground coal mine: shafts, drifts and vents



Source: Adapted from Kentucky Geological Survey, University of Kentucky, United States

Good practice techniques for post-mine drainage can capture 50% to 80% of the total gas from a longwall district in the absence of unusual geological conditions. In practice, 30% to 50% gas capture from an entire mine is achieved in most cases. Methane concentrations of 30% and higher should be achievable using post-mine drainage systems in all but the most challenging mining conditions. Methane concentrations of 60% and higher should be achievable using pre-mine drainage methods.

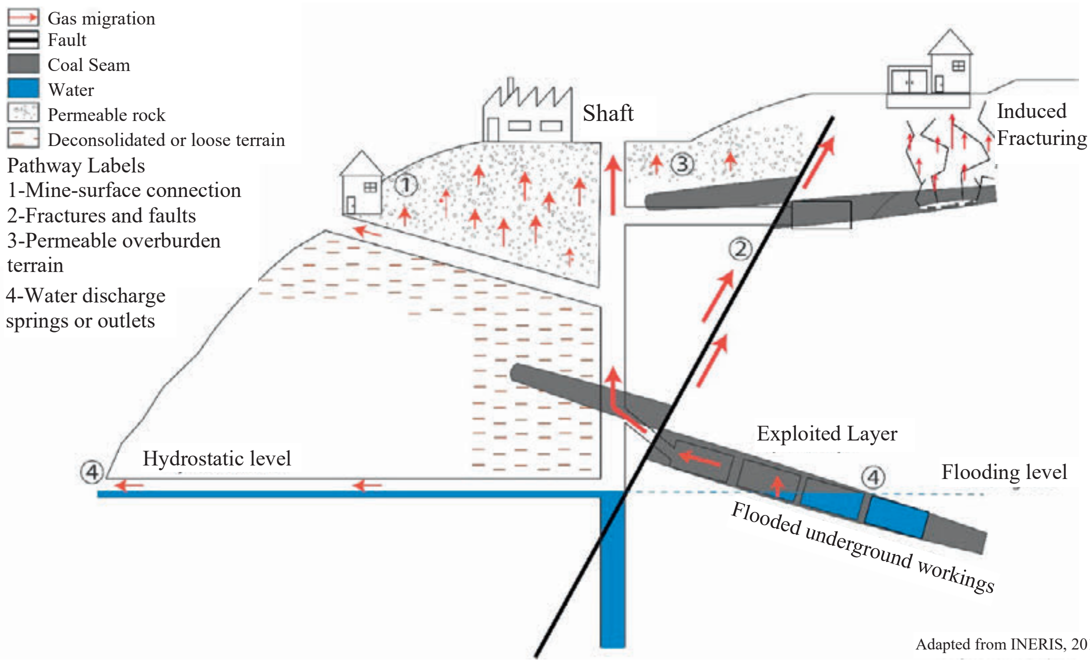
For further information on mine ventilation and gas drainage, see the *Best Practice Guidance on Effective Methane Drainage and Use in Coal Mines* (ECE Energy Series No. 47 and ECE/ENERGY/105) and Modules 5 and 6 of the GMI's interactive training course on conducting pre-feasibility studies for CMM projects (UNECE, 2017; GMI, 2021).

2.3 Abandoned mines

When a mine is abandoned, all services are severed, including ventilation. Gas that was formerly segregated between the CH_4 drainage systems and the ventilation is combined and initial emissions can be high but will decline gradually over time as the sources decay. Groundwater will, in many instances, progressively flood the mine and curtail AMM emissions. Depending on the hydrogeology of the area and local mining conditions, mines can take from a few years to decades to completely flood. Although abandoned mines are often sealed, gas may be emitted to atmosphere. In optimal conditions, these emissions can be controlled through pressure-relief vents, but in many instances, they are uncontrolled as leaks in shaft and drift seals, outcrops, fractured ground above shallow workings, or through underground connections with old workings of other abandoned mines. Uncontrolled emissions from abandoned mines can, in some instances, arise at the surface creating a serious public hazard necessitating remedial measures. The source of such emissions can be difficult to locate and, in some cases, can affect extensive areas.

Figure 2.4

Emission sources and impact of flooding at abandoned mines



Source: Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Mines (UNECE, 2019).

Although abandoned mines can present safety, health and environmental risks, these risks can be mitigated at mine closure through a range of actions including better engineered seals, installation of gas pressure relief vents and use of AMM extraction systems. Control and accurate measurement of AMM emissions can be problematic in mining areas where mine closure best practices have not been adopted and included to mitigate uncontrolled gas emission risks. To learn more about abandoned mines, the gas resources in abandoned mines, and CH_4 recovery from abandoned mines, see the *Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Mines (UNECE, 2019)*.

2.4 Surface mines

Surface mines will release CH_4 from coal and any gas-bearing strata disturbed through excavation. Methane emissions have been reported from surface mines in the United States, Colombia, Kazakhstan and other countries (U.S. EPA, 2014; U.S. EPA, 2008). Although there are some examples of surface mines with significant gas resources, large-scale CH_4 emissions at individual mines are rare. Collectively, SMM emissions appear to be much lower and more diffuse compared to emissions from underground mines. On a global scale they are not known to be significant in terms of CH_4 emissions, but emerging airborne and satellite remote sensing systems should help to reduce uncertainty on the scale of emissions from surface mines. On the other hand, surface mined coal, like underground mine coal, emits large volumes of CO_2 when products are combusted.

Figure 2.5
Surface mine, India

Source: Photostock

3. Monitoring, reporting and verification of methane emissions from coal mine sources

Key messages

- Methane emissions from underground coal mines are emitted at point sources and can be easily quantified, the accuracy depending on measurement methodology and frequency of determinations.
- After abandonment, monitoring becomes more complex due to uncontrolled emissions from different potential sources, which may not be located easily.
- Emissions from surface mines are generally low and diffuse and indirect methods can be used.
- Reporting and verification are essential to ensure policy and mitigation is soundly based.

3.1 Monitoring and measurement of methane emissions from coal mines

This section will present the various methods that have been or could be used to measure CH_4 emissions from working and abandoned coal mines and their perceived strengths and weaknesses. It will also discuss the effects of monitoring frequencies, locations and other considerations for MRV systems and practices. Selection of monitoring locations and the frequency of measurements should take account of spatial and temporal variability in CH_4 flow as described in Chapter 2.

For purposes of monitoring GHG emissions, there are various methods available to monitor CMM, including VAM and mine gas drainage, AMM and SMM emissions, as well as emission reductions. Methods described include the use of emission factors, decline curves, measurements using hand-held instruments, or continuous emissions monitoring systems.

3.1.1 Emission factors applied to coal production at working mines

The simplest monitoring method is to apply an emission factor to coal production. This method is only used to estimate emissions or to establish an emissions baseline at working mines. The method is not relevant for estimating emissions from abandoned mines.

Emission factors are usually denoted as a volume of CH_4 per metric tonne of coal mined, for example m^3/tonne or ft^3/ton (USA) of coal mined. Once a factor is derived, often from historical data, the factor is applied to the quantity of coal produced to develop an emissions estimate.

Emission factors are used to estimate emissions in many industry sectors and, in the coal mining industry, are used widely to estimate national CMM and SMM emissions for emissions inventories. Emission factors are especially used in countries where MRV programmes are not in place or where emissions are relatively minor and difficult to measure, such as those from surface mines and post mining emissions. In instances where quality data on historic CH_4 emissions are unavailable, emission factors have been developed using data from other mines or countries (analog data) that produce coal from seams with similar geologic and geotechnical properties. Without some form of validation from local observations, however, this approach can lead to large uncertainties. Measures should be taken to improve the reliability of such estimates.

Emission factors can also be applied at regional (or basin) and mine-specific scales. Coal basin-specific emission factors are considered to be more accurate than national emission factors. At underground mines, basin-specific emission factors may be obtained from ventilation air measurement data, combining it with available data from degasification systems, including CH_4 collected by the degasification system or the degasification system collection efficiency. Basin-specific emission factors may also be derived from a quantitative relationship derived through modelling that accounts for the gas content of the mined coal seam and the surrounding strata affected by mining.

Mine-specific emission factors refer to the total gas release from all sources in a mine, including working longwalls, abandoned areas, developments and coal on conveyors, all of which are captured in the VAM. VAM quantities are added to drained CH_4 quantities to produce combined mine-wide emissions. Mine-specific emission factors should be determined by measurement over a period of at least a month, avoiding any holiday breaks, to check for consistency of the factors over a sufficient period of time. A review every 3-5 years should suffice, unless there is a major change to the mine structure, in which case a new measurement should be made.

Advantages:

- Emission factors can be developed on a national, regional or mine-specific scale.
- Once established, calculations using emission factors can be performed quickly and at minimal cost.
- The units of measure, e.g., m^3/t, are familiar to the mining industry because the industry uses similar units to measure “specific” (or “relative”) emissions for mine gas management.

Disadvantages:

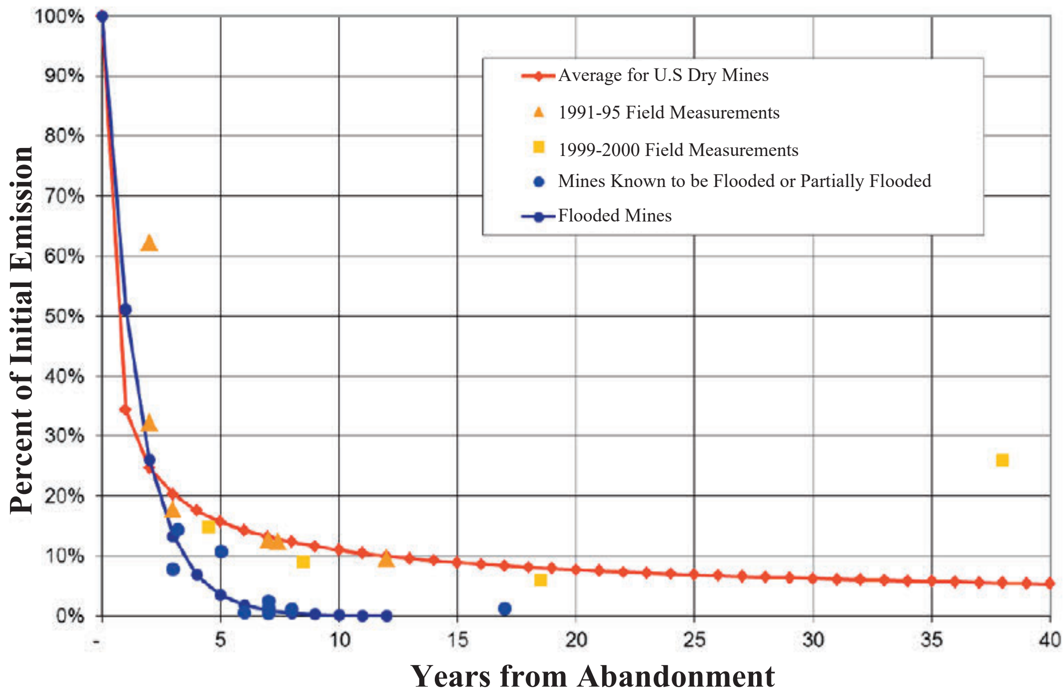
- In general, emission factors do not match the accuracy of direct measurements as a monitoring method and, in some cases, have proven to be very inaccurate leading to substantial over-estimation and/or under-estimation of national emissions.
- Emission factors may not consider the different types of mining, especially at underground mines where emissions produced from longwall and room-and-pillar mines can be vastly different.
- Emission factors are based on data from historical operations that may not reflect current or future operations.
- Development of national and regional emission factors may assume similar gas contents for coal mined across all mines, which is rarely true.
- Emission estimates produced through the use of emission factors might not be suitable for developing policy recommendations or informing mitigation.

3.1.2 Use of decline curves to measure emissions from abandoned mines

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is initially dependent on the mine's emissions when working and later to the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the capacity of the mine to transmit flow. A well or a mine that produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted.

Figure 3.1

AMM emissions decline curves for dry vs flooded coal mines.



Source: Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Mines (UNECE, 2019).

Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modelled by mathematical equations and mapped as a type curve, also referred to as a decline curve. The limited data available on abandoned mine emissions indicate that emissions typically follow a hyperbolic type of decline curve.

Decline curves, ideally developed for specific basins or regions, can be used to estimate gas production at abandoned mines. For a particular mine, the curve is applied to the CH_4 emission rate of the subject mine at abandonment.

Variants of the method demonstrated, for example, in the UK (Kershaw, 2005) and Australia (Lunarzewski & Creedy, 2006) take account of flooding rate in the gas flow predictions.

Advantages:

- Recognised and accepted approach for estimating AMM emissions. Methodology is used by IPCC, U.S. EPA, Australia's Clean Energy Regulator.
- Limited studies employing history matching have demonstrated accuracy of hyperbolic approach.
- Relatively easy to use across large populations of mines once type curves are developed. The starting point is emissions at mine closure. Future emissions follow the curve.

Disadvantages:

- Very limited experience measuring and confirming emissions from abandoned mines.
- Accuracy of national or regional type curves is uncertain.
- One approach assumes abandoned mines are one of three categories: sealed and dry, unsealed and dry, or flooded. However, any deep abandoned underground mine will almost certainly flood over time. Type curves assuming a mine will not flood are unlikely to accurately predict future emissions at abandoned mines.

3.1.3 Measurements using handheld instruments

Working underground mines

A very common method for obtaining gas flow measurements at working underground mines in both the ventilation air (VAM) and gas drainage systems is through the use of handheld instruments. Such measurements are required to meet statutory safety regulations and must be undertaken by a trained, competent person in accordance with recognised procedures. These same data can be used for greenhouse gas monitoring provided they were taken during production shifts. However, safety monitoring is aimed at checking that preset criteria are met whereas emissions monitoring is aimed at quantifying gas flows and concentrations with a high degree of accuracy; therefore, separate measurements are preferable. The latter emission monitoring approach would allow a verifiable methodology to be introduced. While similar measurement techniques are employed and the same trained staff should be involved, the detail, frequency and locations of emissions monitoring may differ from routine safety monitoring.

VAM emissions can be obtained from spot readings of airflow and CH_4 concentration:

- At the base of the ventilation shaft(s), or
- In all return roadways leading to the ventilation shaft, or
- In the fan ducting of the main exhaust fan on the surface.

In all instances, the measurement process will involve multiple anemometer traverses and multiple methanometer readings or gas samples taken across the airway cross-section of known dimension. At main surface fans, pitot readings may be more practicable due to the high flow rates in the duct. Of the options, the simplest approach is to measure airflow and CH_4 concentration in the duct(s) of the main surface fan(s).

Manual gas drainage flow measurements are generally made using a differential flow device together with gas sampling, for laboratory analysis of gas composition, or a direct reading made with a calibrated high reading methanometer. Flow readings are adjusted to standard conditions of temperature and pressure.

The most common types of instrumentation and measurement procedures that can be used in mines to obtain the CH_4 emission quantities are summarised in Appendix 1.

Hand-held instruments are only suitable for low frequency measurements from daily to monthly, quarterly or annually. The more frequent the measurement, the greater the accuracy because of the variability of gas flows from variations in strata properties, coal production rate and other mine activities.

Abandoned mines

Gas flows from an abandoned mine decline over time as there is no mining activity to create new gas sources. Methane flow measurements can help to define and refine the decline curve; often a regionally derived curve is used as a starting point.

Handheld measurements can be taken at abandoned mines if the mine has a dedicated vent stack or open boreholes, but the results are generally highly variable due to changing atmospheric pressure. The same limitations that apply to using handheld equipment to measure emissions from drainage systems also apply to taking measurements at abandoned mines. In some instances, health and safety authorities or the authority responsible for post mining liabilities may also require regular monitoring of CH_4 emissions from abandoned mine vents. This may be especially true at locations where there is a risk of AMM migration into buildings or where vents release CH_4 into densely populated areas. These same measurements could also be used to estimate CH_4 emissions from an abandoned mine. Spot measurements can be taken manually at the same time as maintenance and inspection visits to service vents, flame traps and check security (e.g., see **Figure 3.2**). However, measurements at vents may not necessarily reflect the full emission if there is a potential for other diffuse CH_4 emissions throughout uncharted emission pathways from the mine workings to the surface.

Figure 3.2

Measurements at degassing vents at an abandoned mine in Germany

Source: Research Center of Post-Mining at the Technische Hochschule Georg Agricola, Germany

Surface mines

The presence of CH_4 can be detected in surface mines by testing for gases, with a methanometer, in blasting boreholes or any surface fractures, but quantitative monitoring using conventional hand-held devices is not practicable.

Advantages:

- Affordable as labour, equipment and lab analyses are not expensive at lower sampling frequencies.
- Widely practiced in the mining industry for health and safety protocols. Experience and know-how can be readily transferred to GHG emissions monitoring.
- Can deliver useful data for identifying mitigation opportunities.

Disadvantages:

- High frequency sampling is impracticable, labour-intensive and expensive.
- Relies on staff competency to take measurements and obtain gas samples correctly.
- Proper care and calibration of instruments is essential, otherwise sampling is likely to produce misleading results.
- Taking measurements outside of normal operating conditions can also produce misleading results.

3.1.4 Measurements using continuous emissions monitoring systems (CEMS)

Working underground mines

Continuous emissions monitoring systems (CEMS) can provide the most accurate measurement of CH_4 emissions from both drainage and ventilation systems but can also be expensive to implement. However, most modern underground coal mines already have continuous environmental monitoring systems providing real-time management information to on-site and remote monitoring stations on the surface (e.g., mine offices, gas drainage pump stations); the benefits to mine management and the safety of operations far outweigh the cost. The data will include airflow and gas concentrations at key underground locations and fans together with gas drainage quantities, pressures and temperature. Effective mine monitoring systems are supported by planned maintenance and calibration services. Maintenance and calibration are key since drainage pipes and ventilation airways can carry substantial amounts of coal dust, other mineral particulates and moisture that can interfere with sensors and distort readings. Velocity and CH_4 transducers used underground must also be compliant with the required electrical standards for intrinsic safety and explosion prevention. However, standard laboratory gas analysers, such as infra-red, can be used at the surface where gas samples are drawn from the mine in a “tube-bundle” or from the surface fan ducting to a nearby building in a designated low risk zone. Most mine regulatory systems set a maximum safe CH_4 concentration permitted to pass through a fan. Continuous monitoring of CH_4 concentration at the main surface exhaust fan, therefore, offers important safety benefits.

Figure 3.3
Installation of real-time air velocity monitoring on main fan ducts.

Source: Belle, 2014

Tube bundle gas monitoring systems comprise a network of tubes through which samples are drawn from key locations to the surface for gas analysis (Belle, 2013). There is a lag between the sample time and the analysis time, which can be estimated. The principal use of this technology is for monitoring spontaneous combustion risk and for facilitating CH_4 monitoring in the event of power loss to continuous CH_4 monitors due to a fire or explosion which damages the in-situ monitoring equipment. Belle (2013) reports that the measurements are reported to be quite accurate, although they may not accurately reflect constantly changing conditions underground, which can be critical for safety considerations.

It is also important to note that gas being drained or emitted into the mine workings may contain heavier gaseous hydrocarbons, such as ethane or propane. These hydrocarbon species can distort the response from conventional infrared-based gas detection systems and cause inaccurate measurement of CH_4. Care should be taken to select monitoring equipment that is capable of correcting for non-methane hydrocarbons so that accurate measurements are ensured (UNECE, 2016). Laboratory gas chromatography is used to determine a full hydrocarbon analysis using gas samples taken in the mine and sealed in a special container.

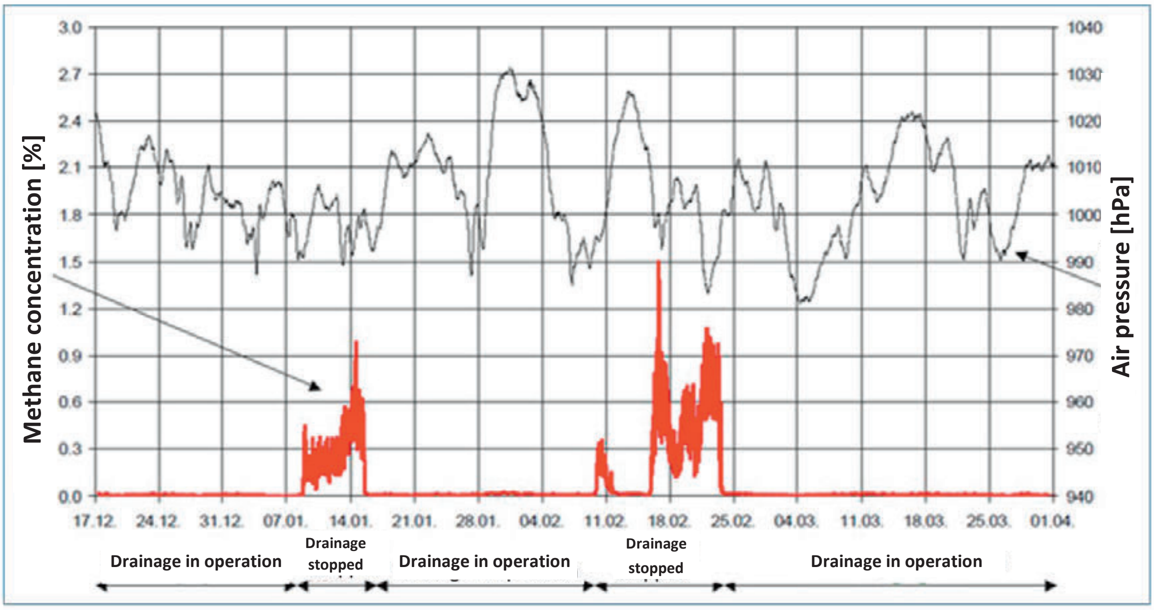
Abandoned mines

Implementing CEMS at identified surface emission locations at abandoned mines can be challenging, as there is often no power supply at abandoned mines to provide lighting and supply support structures such as offices and equipment rooms. CEMS is more practicable at abandoned mines that are connected to the grid or have a stand-alone generator to supply an AMM-use project. For example, power is often available for continuous monitoring of gases at the surface where the AMM is utilised in a cogeneration plant.

Germany has extensive experience with implementing CEMS at abandoned mines, particularly, where uncontrolled migration of AMM into buildings poses a safety risk to the public. To ensure public safety, the mining authority can request the installation of a continuous monitoring system in an affected building (see **Figure 3.4**) and the implementation of gas control measures, such as a gas extraction system which applies suction to old workings beneath the building (Möllerherm, 2021).

Figure 3.4

Monitoring CH_4 concentration in a basement using a fixed measuring device, showing CH_4 concentrations with and without suction being applied



Source: Möllerherm, 2021

CEMS is still feasible even if an external power supply is not available. Battery powered flow and CH_4 concentration monitoring equipment can be used as an alternative with backup data storage and telemetry to transmit the results. Such equipment is sometimes employed to gather data for assessing uncontrolled emission risk or as part of an AMM utilisation feasibility study.

Advantages:

- Much more accurate than periodic sampling or use of emission factors.
- Many mines already employ continuous monitoring for safety purposes.
- Does not require significant human resources to manage.
- Can be used to evaluate mitigation opportunities at specific mines.
- Only acceptable option for emission trading schemes where data quality is paramount.

Disadvantages:

- Can be expensive compared to other methods. Costs may outweigh benefits if installed only for MRV purposes depending on objectives of the monitoring programme.
- Relies on staff competency to interpret data correctly.

Considerations:

- Proper care and calibration of instruments is essential, otherwise misleading results are likely to be produced.
- Standards and compliance procedures must be in place to ensure maintenance and calibration occur.
- Where carbon fees or taxes are charged for CH_4 emissions, CEMs may be the only acceptable monitoring approach due to the necessity of obtaining the most accurate data on which to base fees and taxes.

3.1.5 Monitoring frequency

Monitoring frequencies can dramatically impact measurement results and will vary depending on jurisdiction and objectives of the MRV programme. **Table 3.1**, below, shows options for monitoring frequencies and important considerations for each option.

Table 3.1

Considerations for chosen frequency of monitoring CH_4 at coal mines

Monitoring frequency	Considerations
Continuous	• Uses continuous emission monitoring systems, which may involve a network of tubes with sensors, or specifically sited sensors, along the mined areas that deliver information to a central unit • Determine "continuous" frequency, e.g., every minute, 5 minutes, 10 minutes, depending on instrument sampling frequency and the inherent variability of the data • Most accurate available methods, subject to proper calibration and use • Most conducive to real-time direct data transfer to relevant authority • Highest cost compared to other available methods • Requires regular calibration of instruments and rigorous training to operate equipment and interpret data
Daily	• Uses spot measurements taken with handheld instruments (24-hr pass satellite remote sensing a possibility, in some cases) • Measurements should be taken during normal operating conditions • Expensive as it requires a full-time technician to take and interpret measurements daily • Produces large volume of data that might not be necessary to achieve the policy objectives • Requires regular calibration of instruments and rigorous training to operate equipment and interpret data
Weekly	• Uses spot measurements taken with handheld instruments • Measurements must be taken during normal operating conditions • May be optimal monitoring frequency for spot measurements. Less expensive than daily measurements – 20% of technician's time – and manageable volume of data that can be readily compiled and reviewed by the mine staff, the public, government agencies, and other stakeholders • Requires regular calibration of instruments and rigorous training to operate equipment and interpret data
Monthly	• Uses spot measurements taken with handheld instruments • Measurements must be taken during normal operating conditions • Less representative than more frequent measurement but not overly burdensome for reporting mine or entity • Requires regular calibration of instruments and rigorous training to operate equipment and interpret data
Quarterly	• Uses spot measurements taken with handheld instruments • Measurements must be taken during normal operating conditions • Less representative than more frequent measurements • Very low burden on reporting mine or entity • Requires regular calibration of instruments and rigorous training to operate equipment and interpret data

Annually	• Uses spot measurements taken with handheld instruments • Measurements must be taken during normal operating conditions • Extremely low burden on reporting mine or entity • Requires regular calibration of instruments and rigorous training to operate equipment and interpret data • Very low accuracy and of questionable benefit as the measurement may not be representative.

3.1.6 Other considerations for emission monitoring

Working underground coal mines

Underground coal mine activities include monitoring of CH_4 concentrations, airflows and gas drainage flows for operational and safety reasons. Relevant data may be available from both manual and continuous monitoring sources. While such data can be useful for GHG estimations, barriers to gathering these data can arise, such as secrecy cultures. Secrecy cultures may arise due to fear of punitive action by safety regulators, government departments with unrealistic CH_4 concentration targets (especially on state-owned coal companies), or due to inter-company competition. Mandated inclusion of mine emissions in national or subnational GHG reporting can help obtain better data for decision-making and ensure that realistic policies are set that meet less resistance. Additionally, required use of independent third-party verification can provide credible and defensible quantification of emissions data.

Due to the variability of CH_4 concentrations in mine air and mine gas drainage systems, CEMS are required when generating environmental commodities such as Certified Emission Reductions (CERs) under the Clean Development Mechanism (CDM) and Joint Implementation (JI), or other emission trading schemes. To ensure total integrity, project developers usually install, operate and maintain monitoring and data management equipment and systems independently of the mine operational and safety information systems. In addition, project developers must ensure that installed equipment adheres to strict monitoring protocols, as for example, described in the UNFCCC approved consolidated methodology for "abatement of CH_4 from coal mines" (Appendix 2). Periodic monitoring does not provide the rigour and confidence in the measured data to underwrite such emissions trading programmes. However, periodic monitoring can be sufficient for national GHG reporting programmes where such a stringent approach may not be necessary to achieve the programme's objectives.

Abandoned mines

Emissions from individual abandoned mines can be monitored at pressure-relief vents, where installed, in which flows are variable and dependent on rates of change of atmospheric pressure. However, emissions from poorly sealed mine entries, unknown mine entries, unsealed gob wells and from surface seepages, sometimes over large areas, cannot be easily determined. Although a significant nuisance and hazard, fugitive emissions at abandoned mines may not be as large as those at working mines. For example, based on decline curve estimates, Australia's abandoned mines account for

4% of annual national coal sector emissions, and in the United States, AMM accounts for 11% of annual national coal sector emissions (Australia DISER, 2021; U.S. EPA, 2021)[2].

Many countries face challenges in quantifying national CH_4 emissions from abandoned mines. While some monitoring of abandoned shafts exists, it is by no means universal. Methodologies for assessing emissions of AMM have been developed by various organizations in different countries (e.g., U.S. EPA, the Department of Environment, Food, and Rural Affairs (Defra) in the UK (Kershaw, 2005), Clean Energy Regulator in Australia). These methods are based on modelling assumptions or hybrids involving model forecasts together with measured data from vents. When mines are abandoned, groundwater pumping ceases and the mine workings progressively flood. Suitable methodologies take account of groundwater recovery rate. Further details of current approaches to quantification of AMM emissions are described in Appendix 3.

Surface mines
Measurement of SMM emissions is challenging due to their diffuse nature over a wide area. Emissions from surface mines are rarely directly measured, although the technology exists. A tier 1 emission factor (IPCC methodology) is commonly used and the CH_4 emission quantities, in most instances, tend to be low in comparison with deep mines and therefore uncertainty is not a major concern. One approach to producing a more reliable result is to measure the gas content of the seams (sampled from exploration borehole cores) extracted or disturbed and to assume 100 percent of the gas is emitted. This method might underestimate emissions by excluding any gas from pore and fracture space but could be adjusted by applying a correction factor. Post-mining emissions can also be incorporated by using the total gas content in the calculation. Another approach to direct measurements of average CH_4 concentration in a surface mine is by using long-path infrared or similar instruments, but this method is generally undertaken as research projects.

3.2 Reporting of emissions from coal mines

Reporting is an essential tool that should accompany and be complementary to any monitoring activity. Reporting allows stakeholders, including the emitting facilities, to track changes in emissions and emission reductions over time more easily and effectively. Users of reported data may also gain insight into particular operating or commercial conditions that can impact emissions at individual facilities or in the broader mining industry.

Reporting can be of two kinds: (1) nationwide or regionwide inventory reporting and (2) facility-level reporting. For inventories, reporters are normally government agencies or other entities that collect, calculate and analyse monitoring data to prepare the national inventories. National GHG inventories are reported to the UNFCCC, while sub-national inventories are reported to the relevant authority at the national or provincial level.

[2] Estimates based on decline curves may be understated as examples have arisen where more gas has been extracted than predicted from the decline curve.

At the facility level, reporters are typically the owner/operators of working mines, abandoned mines or mitigation projects. Facility-level emissions and emissions reduction data may be reported to:

- an environmental regulatory agency
- mine health and safety authorities
- a voluntary or regulatory emissions trading programme
- a non-governmental entity such as an industry association, or
- an office or division within a mining company charged with tracking GHG emissions or managing environmental, social and governance goals.

Reporting systems aid in receiving and processing reported data, serving two important functions: (1) they compile large quantities of measured or calculated data into concise, representative reports, and (2) they provide structured and reliable frameworks for submitting and receiving reports. These functions ensure transparency among reporting programmes. Ideally, users will have access to adequate training for accessing and appropriately using reporting systems to support correct and consistent reporting while reducing the time and cost burden on reporters.

Reporting systems can compile the raw data obtained through monitoring and measurement into digestible formats for more effective use by reporting facilities, national inventory preparers, regulators, policymakers, the public and other stakeholders. This is an essential function, because emissions data are often collected in large, complex data sets that may be stored in different media formats, recorded in differing units, and taken in varying time series. Simply transferring raw data without context provides little or no value to the preparer and the user. An effective reporting programme, thus, provides a well-organized template or reporting form to ensure consistency in reporting.

Basic good practice principles for CMM/AMM/SMM emission reporting require that a reporting template or reporting form be:

- readily comprehensible to reporters, those receiving the report and other users
- manageable for a reporter to navigate and complete
- comprehensive enough to capture important facility information and critical emissions data
- designed to accurately present supporting data sets that underpin emission estimates
- complete enough to, at a minimum, provide net emissions values for the entire facility and, at best, identify all emission pathways and emission reductions from all mitigation activities
- sufficiently clear such that quantitative methods and emission factors are easily identified and can be used to identify potential data gaps

Examples of existing CMM, AMM and SMM reports and reporting forms include UNFCCC ACM0008 project design documents and monitoring reports[3] and the USGHGRP reporting form for underground coal mines[4].

Objectives for reporting programmes vary, and thus, the level of detail in reports will vary to meet the reporting parameters established by the authorizing entities. For example, reporting could consist of providing a single annual CH_4 emissions value or a coal production quantity multiplied by an emission factor. Alternatively, it could provide detailed data on CH_4 concentrations, flow rates and other factors at all point sources at a mine over multiple measurement periods based on prescriptive or performance-based requirements with emissions based on detailed calculation methodologies.

Access to more data is often preferred over less data. But large volumes of data might not be easy to manage, particularly if using paper forms. It is good practice to balance the added value of evermore detail with the overall objectives of the reporting programme and the burden placed on reporters to obtain, compile, and report the data. It is also important that the data be used productively to justify the burden placed on the reporting entity to obtain and report the data. Simply requiring facilities to report data without making further use of reported data risks the programme being regarded as punitive rather than productive.

Reporting programmes can also require reporting facilities to retain supporting records and make them available for inspection rather than requiring reporters to compile significant volumes of data in reports. In these instances, it is critical to the programme's credibility for the programme to follow up and audit supporting records.

Reporting systems should also provide a structured and reliable framework for transferring data. They can rely on paper or electronic submissions and can require reporting at different frequencies (e.g., quarterly, annually), even where monitoring may be on a more frequent basis. For example, a reporter might monitor emissions continuously or daily but report only once a year. Irrespective of the monitoring attributes, an effective programme will have established procedures and systems in place for preparing, certifying, submitting, and accepting reports. Certification, in particular, is an important step in the submission process because it requires the owner/operator or other legally responsible party to acknowledge that it has reviewed and understands the data reported therein and certifies to the accuracy of the data. It also requires that the reporter tacitly or implicitly acknowledge that data acquisition and emission measurements and calculations are in compliance with established requirements.

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[3] See example: Duerping Coal Mine Methane Utilization Project (https://cdm.unfccc.int/Projects/DB/TUEV-SUED1214838535.8/view)
[4] See subpart FF reporting form: https://ccdsupport.com/confluence/display/help/Reporting+Form+Instructions

An example of an online GHG reporting system is the USGHGRP Electronic Greenhouse Gas Reporting Tool (e-GGRT) used by reporting coal mines in the United States.[5] Reports are not considered to be formally submitted until certified by an officially designated representative of the facility owner/operator who was previously approved by the Program administrator.

Other considerations in establishing a reporting programme or system include:

- **Reporting burden:** It is important to consider whether the required information is purposeful and does not overburden reporters, which is important to ensuring acceptance among reporters. Therefore, government agencies should ask:
    - Does the additional level of granularity and incremental level of effort achieve the stated goals of the reporting programme?
    - Does the required level of effort provide commensurate confidence in emissions data and insight into facility, regional or nationwide CH_4 emissions?

- **Reporting thresholds**: Not all mines are gassy. Therefore, government agencies should consider whether to require all mines to report or focus only on those mines that contribute the largest share of emissions. The decision will likely depend on the purpose of reporting. If the objective is to develop a comprehensive inventory of CMM, AMM and SMM emissions, then it may be advisable to require that any gassy mine report emissions. On the other hand, if the objective is to understand the sources contributing the majority of emissions or emission reductions, then a reporting threshold may be the most effective policy tool. For example, the USGHGRP has a reporting threshold of 36.5 million cubic feet of CH_4 per year (~1.03 Mm^3) or around 17,025 tCO_2e. Underground coal mines with emissions below this level are not required to report. This threshold resulted in only 67 out of 226 working underground mines reporting in 2019, but those mines accounted for 92% of the United States' total estimated CH_4 emissions from underground mines that year (Talkington, 2021).

- **Applicable global warming potential:** The Global Warming Potential (GWP) for CH_4 changes with each IPCC Assessment Report (AR). The GWP in AR3 was 21, in AR4 it was 25, and in AR5 it was 28-34 over a 100-year time frame.[6] In addition, CH_4 has a significantly higher GWP over a shorter time frame due to its shorter atmospheric life relative to CO_2. The variety of GWPs has led to differing emissions assessments, forecasts, and mitigation estimates. It is, therefore, critical to clearly establish the applicable AR used for a reporting programme and to be completely transparent when changing GWPs.

- **Indirect emissions, emission reductions and non-methane organic compounds:** For reporting of emission reductions, reporting programmes must determine

[5] U.S. EPA Electronic Greenhouse Gas Reporting Tool (e-GGRT): https://ghgreporting.epa.gov/ghg/login.do
[6] Compared to CO_2

whether to focus solely on CH_4 or include emissions from non-methane organic compounds (NMOCs) and CO_2 emissions from combustion of CH_4 (and potentially NMOCs). However, a reporting programme can also consider the benefits of indirect emission reductions from CMM, AMM and SMM mitigation projects resulting in displacement of coal-fired electricity generation or thermal heating.

- **Coordinating data collection with other programmes:** Reporting programmes may provide the opportunity for reporting entities to collect data relevant to multiple programmes. For example, underlying emissions data such as air flow and CH_4 concentration data may be of value to mine safety and environmental regulatory authorities.

3.3 Verification of emissions data

As part of its internal policies and procedures, a reporting entity should implement a formal Quality Assurance/Quality Control (QA/QC) programme for an independent review of an emission or emission reduction report before it is formally submitted. By self-certifying a report following internal QA/QC procedures, an obligation is placed on the reporter to affirm the accuracy of the data to the best of its knowledge. However, mistakes do occur, and data gaps can exist. Verification of the data by the non-reporting party, therefore, becomes the third critical component of MRV.

Verification is an important and necessary step to ensure the veracity of reported data as well as consistency and compliance with any reporting requirements. It is especially important for public acceptance of the data and to provide policymakers with the confidence to formulate policy based on reliable data.

Verification can take many routes but generally entails review and confirmation of the data by the party receiving the data or by an independent third party to confirm the accuracy of the reported data. These third parties may be certified by the relevant authority to review and verify reports (legal or voluntary), or they may be organizations with vested interests in CMM, AMM and SMM mitigation projects, such as a bilateral or multilateral financing institutions. A third and very important category of verifiers are representatives of the general public such as public interest groups or non-governmental organizations.

The level of verification depends largely on available resources and the purpose of verification. For example, verification of emission reduction reports in regulated or voluntary emissions trading schemes is normally carried out by independent and authorised third party verification bodies. The reviews are very thorough, follow prescriptive standards, and usually entail a site visit to the facility to inspect records. These reports may be subject to an additional verification review by the authorised authority following the third-party verification. Significant financial value may be tied to the emission reductions through carbon offset programmes, GHG cap-and-trade programmes, carbon taxes or other carbon-related fees. Therefore, it is in the public interest to ensure the validity of the emission reductions through a very detailed review. Although there is a substantial cost for this level of verification, the costs are borne by the reporter.

For larger provincial, regional or national emission reporting programmes, verification of reported data is typically conducted by the government agency responsible for the MRV programme following submission of reports. The time allowed to complete the review of all reports may be limited due to budgets, policies and procedures, necessitating focus on a subset of reports or specific data elements within the reports. Examples of verification techniques are shown in **Table 3.2**.

Table 3.2
Example verification techniques

Verification technique	Details
Aggregated data comparisons	• Compare to known data benchmarks such as changes in coal production • Compare to a facility's reported data from prior reporting years • Compare the reporting facility's emissions against other facilities in the reporting year • Compare reported data to external data sources at the facility or regional level
Data and calculation inspection	• Review for outliers in reported emissions, population counts or activity counts against industry averages • Independently run data inputs through required or standardized calculations to assess accuracy of reported data • Visit the facility to review records to confirm reported data or conduct an independent measurement
Independent check	• Require certified, third-party verifiers review data at individual facilities • Utilise remote sensing data obtained though aerial and satellite surveys (see section 3.3.1)

Whether the verification is very detailed like those undertaken for emissions trading schemes or is conducted at a higher level such as for national reporting, it is very likely that there will be additional correspondence between verifiers and reporters as part of the due diligence process. This may result in changes to the original report, including upward or downward adjustment to reported quantities of emissions and emission reductions.

Following verification, release of reported data provides additional verification options, including public review of the data.

3.3.1 Advances in verification using remote sensing methods

Remote sensing methods, such as satellite and aerial technologies, have not yet been used to quantify emissions for national monitoring of CMM, AMM or SMM, but advances have been made in using these technologies to estimate site-specific quantities of emissions of CMM, AMM and SMM, enabling these technologies to be used to verify ground-based measurements and estimates. The potential for use of these technologies for verification is promising and has been demonstrated in numerous studies (see Barkley, 2019; Miller, 2019; Varon et al., 2018, Varon et al., 2019); however, it is an emerging topic for verification of national inventories.

Obtaining emissions data from remote sensing technologies is easiest from working underground mines and particularly, from the degasification systems of such mines where sources of CH_4 are more concentrated. This approach may also be feasible for diffuse sources such as surface coal mines, diluted CH_4 from ventilation shafts of working underground mines, and acute seepages of AMM. It is important to consider variability of CH_4 concentrations and flows, as emission results obtained through remote sensing might not match emissions measured on the ground at a different point in time.

Remote sensing of CH_4 concentrations can be done either in-situ or through satellites. In both techniques, an imaging sensor, able to detect CH_4 emissions, is attached to a satellite, an aircraft or another vehicle that follows a pre-determined travel trajectory. An imaging sensor can be of two types: passive, which relies on the quantifying absorption and reflectance of sunlight (which is known and cyclical), and active, which quantifies absorption and reflectance of a targeted laser (light detection and ranging, or lidar).

Many factors go into interpreting the collected data and expressing it in terms of emission volume or rate, such as the choice of calculation methods and algorithms that classify differences in measured absorbed irradiation. Each approach carries its own unique set of uncertainties, not all of which are yet fully understood or quantified.

Satellite observations
Satellites offer several advantages to obtaining emissions monitoring, such as ability to track emissions independently of the source and to provide recurring estimates over large geographies. Initially, satellites were used to detect large-leak events, which release a lot of CH_4 at a given point in time, but recent developments in sensor technologies and satellite image analysis have been made in using satellites for characterizing emission rates and sources. Most of the research has been concerned with CH_4 emissions from oil & gas infrastructure, which is mostly above ground and traceable by satellites, but over the past five years CH_4 emissions from coal mines also received attention.

The advantages of emission estimates using satellites depend on the type of instrument used. Satellites can provide *global, regional*, and *targeted* coverage (see Appendix 4 listing satellite systems capable of observing CH_4 emissions). Usually there is trade-off between coverage, spatial resolution, time scale and cost. Satellites that are global cannot have fine resolution (pixel size), while targeted satellites might not be capable of offering global coverage or frequent return time, unless a system of satellites is employed.

Satellites capture data from the surface and the atmospheric column in form of pixels, each of which has multiple quantitative attributes showing ***reflectance differences*** between surfaces and the atmosphere, i.e., how much light is reflected vs. absorbed along the electro-magnetic spectrum, compared to the radiation from the sun that the Earth receives (which is cyclical and known). The higher the density of CH_4 in the atmospheric column, the less radiation is detected at the Earth's surface in each pixel, which can be a factor that indicates high emissions.

Combining and interpreting pixel attributes through ***analytical algorithms, or indicators,*** is an important aspect of quantifying CH_4 concentrations. Such algorithms aim to highlight the differences in the reflection of different wavelengths and eliminate the impact of certain features, such as clouds, buildings and water, that can result in anomalous pixel values. In addition to analysing pixel attributes, CH_4 quantification must rely on ***air pollution dispersion/transport models*** to understand movement and sources of CH_4. The most common models are the Gaussian plume inversion and pixel mass balance, but there are other models promising greater accuracy, including integrated mass enhancement (IME).

Calibrating satellite observations with data from land-based monitoring can improve the accuracy of satellite data. Data processing companies claim to have made advances in automated interpretation of geospatial data from satellites and in combining such data with other public and private information to distinguish between CH_4 from coal mines and other CH_4 sources, such as oil and gas operations, enabling regional evaluation of emissions and detection of large-scale leaks (Barré et al., 2020).

For facility-level emissions, newer high-resolution commercial satellites can cover the desired area and collect the CH_4 emissions data. GHGSat, for example, currently has three high resolution satellites and is expanding to a constellation of ten satellites, which will be able to deliver information at the facility level (see **Figure 3.5**). Other non-profit and commercial providers anticipate launching satellites for CH_4 monitoring (e.g., Environmental Defense Fund, Bluefield, Carbon Mapper) which are at various stages of development.

Using the best available high-resolution satellites for CH_4 monitoring allows for independent verification and spot-checks of vented drained CH_4 and VAM from working underground coal mining operations (Varon et al., 2018). As satellite operators continue to improve and expand the constellations, the capabilities and capacity will increase as well, and are likely to include some surface and abandoned facilities. Today, facilities can be monitored up to weekly; however, by the end of 2022, it is expected that satellite configurations will be capable of taking daily measurements for CH_4 emissions at the facility level.

Figure 3.5

Methane concentrations above atmospheric background from four working coal mine vents, March 31, 2021, Poland

Source: GHGSat

Establishing acceptance and greater confidence in the ability of remote sensing to verify CMM, AMM and SMM emissions will require a comprehensive evaluation of data acquisition and processing techniques, evaluation of uncertainties, and matching of modelled data to ground observations (Varon et al., 2019). Researchers continue efforts to understand and quantify several sources of uncertainties, which include:

- ***Variability of emissions***. CH_4 emissions from coal mines, and particularly drainage system emissions, have large temporal variability. Emission rates can change over the course of an hour, depending on production rates, geology, atmospheric pressure, etc. This uncertainty is also pertinent to ground observations and can be mitigated by frequent and regular observation times.

- ***Detection uncertainty***. When satellites retrieve column concentrations of CH_4 plumes, the vertical sensitivity depends on atmospheric scattering and absorption of solar radiation. Clear sky and low wind improve CH_4 detection. Separately, it is easier to detect high-emitting facilities with source rates exceeding 10,000 kg/hour (such as from the oil and gas facilities), but more sensitive instruments are needed for detection of low-concentration VAM from coal mines, which are still detectable in the air because of the mass of CH_4, despite the low concentrations at the source.

- ***Mine location uncertainty***. Since locations of mines are often unknown, particularly of underground or closed mines, it can be difficult to precisely identify and attribute the source of emissions.

- ***Source allocation uncertainty***. Another layer of uncertainty is the allocation of CH_4 emissions specifically to coal mines. CH_4 can come from multiple sources, and coal mines are often located next to oil and gas fields, as in the Appalachian region. One example of this uncertainty is estimates of CH_4 emissions in the Bowen Basin in Australia by Kayrros. The data analytics company spotted two large clouds of CH_4 over the Bowen Basin on June 21, 2021 that were visible across more than 30 kilometres (km) each. The plumes were diffused, and there was large uncertainly regarding their source, however, Kayrros attributed the plumes to coal mining. Queensland's Department of Environment and Science stated it did not receive notice of CH_4 releases from the mine (Bloomberg, 2021). To reduce this uncertainty, data can be obtained from higher-resolution targeted satellites in combination with more frequent measurements.

- ***Quantification uncertainty***. To quantify CH_4 emissions from point sources, researchers need to use different techniques to translate satellite data on solar radiation reflectance and absorption into CH_4 concentration and volume. GHGSat is currently demonstrated to have the most precise instruments for detection and quantification of mine methane emissions. One study showed that the best air pollution dispersion models can infer source rates with an error of 0.07-0.17 t/hour +5-12% depending on instrument precision (1-5% for GHGSat instruments) for integrated mass enhancement (IME) method), and 0.07-0.26 t/hour +8-12% for the cross-sectional flux (CSF) method (Varon, 2020).

In any case, confidence in satellite data on coal mine emissions is likely to be more accepted if it is combined with other data, including from CEMS.

Aerial surveys

Aerial surveys have many of the similar characteristics and limitations as satellite observations, described above. Aerial surveys are more commonly used to quantify smaller scale emission sources, as they reveal more detailed insights at finer resolutions and distinguish among seemingly contiguous sources. Aerial data can provide an intermediary link between satellite measurements and bottom-up inventories and can also serve as an independent assessment of drained CMM, VAM and SMM emissions at the facility level.

Research on application of aerial surveys to coal mines has covered the use of both passive and active sensors. Aerial survey of CMM using passive sensors was pioneered by the MAMAP (Methane Airborne MAPper) (Krings et al., 2013). The MAMAP CH_4 column observations allow for accurate assignment of observed fluxes to small clusters of about 20 individual point sources. It is a grating spectrometer, which records backscattered solar radiation (shortwave infrared) from the ground while flying above the layer in which the emission sources are located. Collected data on absorbed radiation is interpreted in terms of CH_4 emissions. The precision of the instrument is sufficient to investigate CH_4 emissions in the regions with highly concentrated point sources, such as CH_4 from drainage vents and VAM, as it can quantify small emission ranges. For CMM flux estimation, these instruments require wind speed and direction obtained from a wind lidar system deployed in different locations. The advantage of imaging airborne detection and quantification of CMM emissions is that images of atmospheric CH_4 distributions allow the detection of locations with unexpected leakages. A disadvantage is the technique is operable in daylight only in clear air.

In contrast to passive remote sensing, active remote sensing using lidar (light detection and ranging) uses a laser as the light source and, thus, is independent of sunlight. Usually, emissions are measured by perpendicularly crossing the emission plumes and comparing the enhancement of the signals with flight legs upwind of the emission source or beyond the location of the plume. Airborne CH_4 lidar systems have mostly been applied to detect fugitive emissions from pipelines or oil and gas installations. CMM emissions have been quantified using the lidar system CHARM-F operated by German Aerospace Center (DLR) (Amediek et al., 2017; Fix et al. 2020) for selected coal mines in Poland. It was found that CH_4 emissions in the order of 9 kt/year can easily be detected from flight altitudes of greater than 6 km. It was found that to accurately measure CH_4 concentration in the column, precise wind information is needed to decrease the overall uncertainty (Wolff et al., 2021). The advantage of lidar is that it is independent of clouds above flight level and can be used during the day and night. It is best to cross the emission plumes in the vicinity of their origin such that emission sources in a tight neighbourhood can be separated from each other.

When it comes to quantifying emissions based on aerial survey data, the most established method is the mass balance approach, which includes observations upstream and downstream of the targeted source and calculates the difference in the volume of emissions as the net CH_4 fluxes. For example, this method was applied to independently assess emissions of CMM from the Upper Silesian Coal Basin in Poland (Fiehn et al., 2020). Using the same collected in-situ data, Kostinek et al. (2021) recently demonstrated an alternative to the mass balance technique, including a combination of aircraft in-situ measurements and a Lagrangian particle dispersion model. This method allows for remotely studying emissions at the facility scale.

Aerial surveys can quantify and attribute CMM emissions from point sources with greater certainty than satellites, including from ventilation shafts and drainage stations. Given variability in CH_4 concentrations and flows from coal sources, these measurements can be matched with ground measurements at the specific times of the survey. For emission verification to be credible outside of the specified points in time, such surveys should be performed regularly. It is important to remember that time and organization requirements can limit the usage of aerial surveys.

Additionally, airborne surveys require very accurate temporal emissions data from coal mining operators, most preferably on a monthly or even more frequent basis. One potential solution would be to create an independent organization to conduct airborne measurements on a regular basis. Alternatively, it is possible to conduct ground-based measurements using drones, which have proven to be helpful when deploying several devices as an *ad hoc* observation system at dedicated locations. Aerial survey methodology is a quickly evolving field and more studies are needed to understand its potential for assessment of MRV data.

4. How MRV supports mitigation of coal mine methane emissions

Key messages:

- Technologies exist for mitigating emissions at both working and abandoned underground coal mines, and there is considerable scope for increasing the number of projects.
- MRV is essential to mitigation, providing policymakers, investors and industry with accurate information to inform decision-making.
- Mitigation can be further supported through dedicated communication on mitigation opportunities identified through MRV and through tools that can support project developers in launching mitigation projects.

4.1 Mitigation at working coal mines

MRV provides robust data that can help determine the full scale of CH_4 emissions from a nation's coal mines, support evaluation of the mitigation potential, and establish the foundation for targeted and supportive policies. Importantly, MRV also facilitates tracking of mitigation action and impact.

Mitigation of emissions from working underground mines
Underground coal mines that are gassy present the largest potential for mitigation as they account for the largest share of emissions from the coal mining industry. Emissions from working underground coal mines can be released either through ventilation systems or gas drainage systems.

Figure 4.1
Gas drainage equipment at Pniówek Mine in Poland

Source: U.S. EPA.

VAM emissions are larger by volume (typically 70-80%) but with very low CH_4 concentrations normally below 1%, which makes mitigation costly. The current mitigation technology removes a proportion of the VAM vented at the main exhaust fan using a device, which oxidises the CH_4, producing CO_2, water and heat. At some mines, the heat has been used to generate electricity through a steam turbine, but additional drained gas is needed to maintain a consistent CH_4 flow rate and concentration. In limited instances, high sales prices for electricity may be able to sustain a VAM project, but generally, VAM projects require the support of carbon pricing or targeted financial incentives to be economically viable.

Alternatively, drained mine gas at CH_4 concentrations of 25% and higher allow for the most cost-effective mitigation projects. Installation of mine gas drainage systems and/or improving drainage efficiency has the potential to increase the share of CH_4 available at higher concentrations, which can be easier to mitigate. MRV programmes can provide insights at the national and/or facility level into the share of drainage CH_4 available for mitigation, which, compared to VAM, is typically the most cost-effective option for mitigation.

Gas drained from underground and brought to a surface pumping station is eminently suitable for utilisation provided the system is managed to maintain gas purity in accordance with best practices. The most common utilisation methods are pipeline transmission of gas to local industry or housing for heating purposes and generation of electricity using gas engines. Unused gas can be flared, which has become more popular in the United States with support of the California Cap-and Trade programme, but globally it is rarely practiced without support from carbon pricing unless mandated.

Conceptually, a combination of VAM and post-mining drainage gas utilisation could lead to near-zero CH_4 emissions from coal mining. The only fugitive emissions would be that which is released from coal at post-mining stages, such as coal handling and processing.

Mitigation of emissions from surface mines

There are limited opportunities to reduce CH_4 emissions from surface coal mines. In a few instances, mitigation of emissions by pre-mine drainage from boreholes drilled in advance of excavation have achieved measurable reductions. Nevertheless, few commercially viable applications have been reported globally and generally, and, to date, mitigation of SMM is not considered viable in most countries. With the growing emphasis on GHG emission reductions generally and CH_4 emission reductions specifically, carbon taxes or emissions trading platforms may provide sufficient price signals to drive greater interest in pre-draining the mined coal strata at surface mines.

4.2 Mitigation at closing and abandoned mines

Closing coal mines is a strategy that would ultimately lead to the largest reduction of life cycle mine CH_4 emissions. MRVs can track declining emissions and coal production at closing mines and whether coal mines are being closed in accordance with regulatory requirements, for example confirming the sealing of shafts at abandoned mines and any mitigation of vented CH_4. MRV can also support quantification of continuing emissions after coal mine abandonment.

Following closure, abandoned mines can present viable CH_4 utilisation opportunities. However, government policy and legislation need to identify a party with responsibility for dealing effectively with post-closure mining liabilities, including MRV, gas licensing and CH_4 mitigation.

Figure 4.2
Monitoring a shaft vent at an abandoned mine in the UK using an encased, portable instrument (foreground).

Source: D. Creedy, 2021

Mitigation of emissions from abandoned mines
Gas produced from abandoned mines can be used in similar ways to the gas drained in working mines. However, CH_4 utilisation is not feasible at all sites; details of how to identify and assess the AMM potential can be obtained from an online GMI training course and also from best practice guidance published by UNECE (UNECE, 2019).

In some instances, CMM co-generation plants installed at working mines can continue operation after mine closure using the AMM. For example, in North Rhine-Westphalia, Germany, more than 100 cogeneration plants had been installed on working coal mines in the Ruhr area and many are still operating, fueled by AMM following closure of all working mines in the Germany (Moellerherm, 2021).

The manner in which mines are closed can affect the ability to recover AMM for utilisation. For example, the mine owner/operator or a project developer working with the mine can prepare the mine for continued gas recovery after the mine closes. The life and productivity of AMM utilisation schemes depend on the magnitude of the gas reservoir, its decline rate and how quickly the mine workings flood as groundwater recovers.

Rapid flooding due to local conditions, or accelerated flooding[7], will rapidly reduce emissions and could form part of a low-cost mitigation strategy in some coalfields. For instance, workings below sea can be quickly flooded by drilling a borehole from the surface.

Where commercial utilisation is not feasible, AMM could be mitigated by flaring, however, special policy provisions would be required to prevent any gas ownership issues with holders of gas-rights.

4.3 The strategic role of MRV in mitigation

MRV can provide governments, industry and the public with a more accurate assessment of CMM, AMM and SMM emissions, emission reductions and mitigation potential. In particular, MRV can be used to support the development of effective policy decisions that address climate change imperatives and to track the impact of the policy. The gains resulting from resolving issues that inhibit project development, such as gas ownership, can also be tracked and assessed using MRV.

MRV in project development

The success of CMM and AMM utilisation[8] and destruction projects is heavily dependent on thorough and accurate MRV. While national or regional authorities may pursue MRV to meet public policy objectives, the CMM or AMM project developer is primarily focused on designing the project at optimal size, maintaining project operation at commercial scale, and generating revenues that can drive profitability.

A robust MRV programme supports the developer's objectives by establishing a clear baseline of gas availability with an understanding of the variation in gas flow rates and CH_4 concentrations. This allows the developer to optimally size the project while also establishing an emissions baseline from which to measure emission reductions through the capture and use of drained CMM, VAM or AMM. A transparent and thorough MRV programme is also necessary to generate cash flow by monetising emission reductions in environmental markets. In some cases, this may be the primary or only source of revenue for the project.

MRV can support more effective CMM and AMM project planning and development, leading to a greater number of successful projects and increased emission reductions, by providing:

- Relevant information to the reporting facility about CMM and AMM mitigation opportunities at the facility.

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[7] Accelerated flooding in this case refers to flooding accelerated by engineering increasing inflows, for example connecting flooded and unflooded workings by drilling a connecting borehole. It does not mean purposefully diverting water into the mine to flood it which could result in contaminating surface and groundwater sources.

[8] SMM utilization is theoretically feasible but has not been put into practice. There are very few instances of SMM utilization, and hence, SMM is omitted from this discussion.

- Detailed facility-specific information to 3rd parties and other stakeholders on mine owner/operator and location, mine operations and historical operations data, gas balance, shaft-specific ventilation capacity and emissions, gas drainage system capacity and throughput, existing utilization project and similar information.

Table 4.1 provides an overview of the information that MRV programmes can provide on CMM and AMM emissions and the potential quality and relevance of such information to mitigation.

Table 4.1

Information from MRV programmes that can support mitigation of CMM and AMM emissions MRV and mitigation resources

Type of Information	Data supporting CMM mitigation	Data supporting AMM mitigation
Emission locations	Specific emission point sources in working mines: • ventilation shafts • gas drainage vents • gas drainage wells	Specific emission point sources: • Vent pipes • Improperly plugged and abandoned gas drainage wells • Abandoned shaft and drift vents Diffuse sources: • Outcrops • Fractured ground above old workings • Unsealed recorded and unrecorded mine entries
Rate and magnitude of emissions	• Mine and point source CH_4 emissions • CH_4 emissions rate (m^3/m) • CH_4 concentration • Rate of coal extraction	• Total emissions at mine closure (initially high but assume decreasing emissions rate over time) • Rate of flooding • Influence of barometric pressure on mine emissions
Measurement method	• Direct from point sources and mitigation projects using calibrated instruments (IPCC Tier 3) on periodic or continuous basis • Mine or basin-specific emission factors (IPCC Tier 2)	• Indirect involving geological, void, water inflow and decline curve modelling (IPCC Tier 2/3). • Direct from point sources and mitigation projects and vent monitoring where available
Uncertainty of assessed quantity	• Low for direct measurement • Medium for use of emission factors	• High for modeling unless there is no good data support • Low to medium for direct measurement
Reporting entity	• Mine owners • Mitigation project owners	• Inheritor of post mine closure environmental liabilities (e.g., the Coal Authority in the UK) • Mitigation project owners
Verification	• Qualified independent third-party • Government department or authorized agent	• Qualified independent third-party • Government department or authorized agent • Peer review as requires specialist knowledge
Factors affective mitigation potential	• Number of shafts and gas drainage collection points available for VAM and CMM drainage projects • Average volumetric flow and CH_4 concentrations for viable mitigation projects	• Number of vents available for AMM projects • Total CH_4 resources • Volumetric flows and CH_4 concentrations at active or sealed vents

	• Potentially available temporal data on fluctuations in flows and concentrations Mining constantly adding new gas resources so gas supply can be steady over a large part of the mine life.	Decaying resource so project life can be short in some instances.
Mitigation opportunities	Based on gas quantity and quality of gas resource, can evaluate mitigation prospects for Use of drained gas for: • Power generation/CHP • Gas transmission/distribution • Direct thermal use • Flaring • Vehicle fuel – Compressed Natural Gas/Liquified Natural Gas (CNG/LNG) • Manufacturing feedstock Oxidation of VAM in ventilation shafts for: • Destruction-only • Heating • Combined Heat & Power (CHP)	Based on gas quantity, quality and extent of capture gas resources can evaluate mitigation prospects for Use of extracted gas for: • Power generation/CHP • Direct thermal use • Flaring
Facility ownership, location and gas ownership constraints	• Should indicate facility ownership and location • May indicate CMM ownership and licensing, while it is common for a mine to have gas extraction rights for safety reasons	• Should indicate facility ownership and location • May indicate AMM ownership and licensing, which may vary between countries (e.g., owned by the government and licensed in accordance with oil and gas exploration and development in the UK)
Mitigation investment risk	Contributes to assessing the gas resource risk for a CMM mitigation project • Medium to low for utilization • Low for flaring offsets where stable, good carbon prices	Primary basis for assessing the gas resource risk for an AMM mitigation project • Medium to high for utilization • Low for flaring offsets where stable, good carbon prices
Information source for further details	UNECE. Best practice guidance for effective methane drainage and use in coal mines. Second Edition, Geneva, Switzerland, 2016.	UNECE. Best practice guidance for effective methane recovery use from abandoned coal mines. Geneva, Switzerland, 2019.

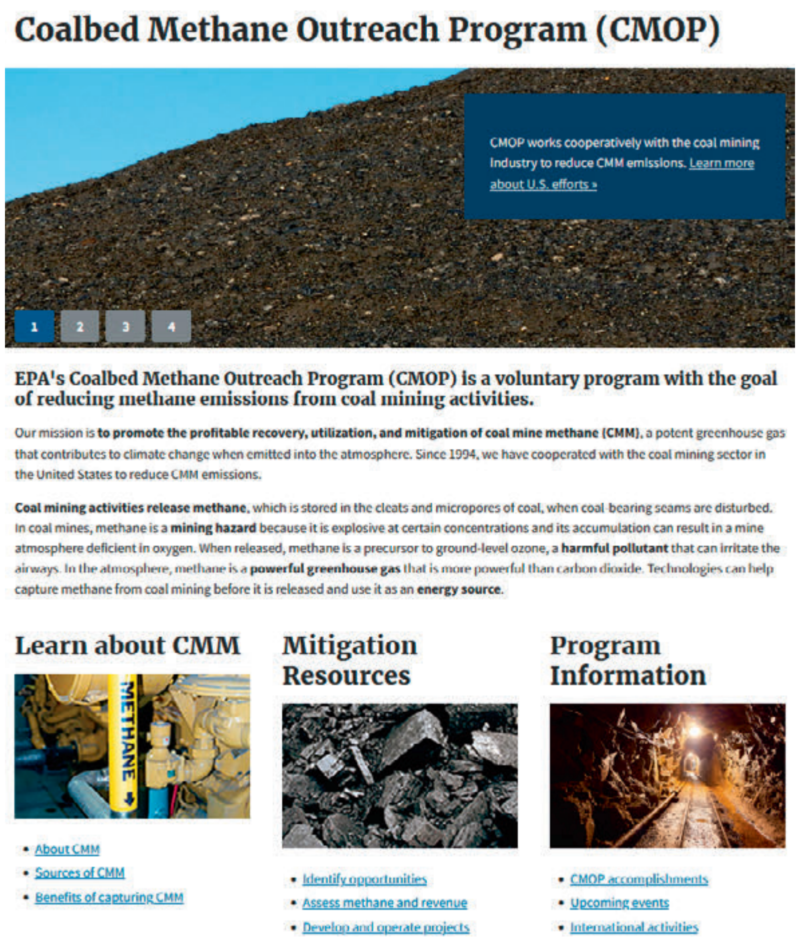
MRV programmes can help identify specific opportunities for mitigation, particularly if facility emission data are available to potential project developers. In addition, governments can support mitigation through enhanced communication of such opportunities and provision of other resources. Tools and resources can be developed to support project developers and mines in completing any or all of the necessary steps to launch a project, including:

- Gathering background Information
- Identifying project opportunities
- Evaluating CMM and AMM resources
- Assessing the market for CH_4 from coal mines
- Analyzing the cashflow or financial flows of a potential project
- Developing and operating a project.

In the United States, U.S. EPA maintains the Coalbed Methane Outreach Program[9], which aims to provide tools and resources for the above-mentioned steps (**Figure 4.3**). For example, CMOP offers a map of mitigation opportunities, based on the information obtained through the national MRV system. The map is accompanied by a report that profiles the 35 gassiest U.S. coal mines as well as a table that includes information on additional mines with gas drainage operations. CMOP organizes webinars on existing technologies and connects with interested stakeholders on CMM, AMM and SMM mitigation. Such voluntary programmes can be an extension of MRV programmes, helping overcome barriers to mitigation and accelerating deployment of mitigation technologies.

Figure 4.3

Example of a government outreach programme for mitigation of CH_4 from coal mining that provides resources based on data collected through a national MRV system



Source: U.S. EPA.

[9] See: https://www.epa.gov/cmop

5. Examples of coal mine methane MRV programmes

Key messages

- A country planning to initiate, or further develop, an MRV programme may be able to accelerate the process by adopting, or adapting, key elements from existing programmes elsewhere.
- Examples from the USA, UK, Australia, China and Kazakhstan are provided in this Chapter covering a wide range of regulatory environments.

5.1 United States Greenhouse Gas Reporting Program (GHGRP)

The U.S. Greenhouse Gas Reporting Program (GHGRP) is a mandatory greenhouse gas reporting programme established in 2010 and administered by the United States Environmental Protection Agency (U.S. EPA). The GHGRP is national in scope and requires reporting of the largest direct sources of greenhouse gas emissions at the facility level. It is a reporting programme only; the GHGRP does not require emission controls. The coal sector has reported under the GHGRP annually since 2011.

Authorizing legislation and regulatory structure

The GHGRP is supported by two legislative actions passed by the U.S. Congress and signed by the President of the United States, which gave U.S. EPA the authority to promulgate regulations to implement the Program: (1) the U.S. Clean Air Act, which authorises EPA to enact requirements to monitor and control air pollutants, and (2) the Fiscal Year 2008 Consolidated Appropriations Act, in which the U.S. Congress included specific authority and funding to initially establish and maintain the GHGRP (H.R. 2764, 2008)[10]. The purpose of establishing the GHGRP as stated in the Appropriations Act is to:

1) Better understand relative emissions of specific industries, and of individual facilities within those industries; and
2) Better understand factors that influence GHG emission rates and actions facilities could take to reduce emissions.

With legislative authority, U.S. EPA finalised regulations in 2009[11] to implement the GHGRP (40 CFR Part 98, 2010), with 2010 being the first calendar year covered. The rules require "reporting of greenhouse gas (GHG) data and other relevant information from large GHG emission sources, fuel and industrial gas suppliers, and CO_2 injection sites in the United States." There are 41 categories of reporters including working underground coal mines.

[10] H.R. 2764; Public Law 110-161. The Appropriations Act required U.S. EPA to ''develop and publish rules to require mandatory reporting of Greenhouse Gas (GHG) emissions above appropriate thresholds in all sectors of the economy of the United States."

[11] Title 40 of the U.S. Code of Federal Regulations Part 98

Role of stakeholders (regulators, facility owners/operators, CMM/AMM/SMM mitigation project owners, the public)

The rulemaking process in the United States is a public process, and all members of the public have the opportunity to review and comment on proposed regulations. Following the close of the comment period, the federal agency reviews comments and publishes final regulations. Rules are then codified in the Code of Federal Regulation and become law. Under the reporting requirements for underground coal mines, key stakeholders have the roles as summarised in **Table 5.1.**

Table 5.1
Roles of key stakeholders

Stakeholder	Role
U.S. EPA	EPA is the environmental regulatory agency that administers the GHGRP. U.S. EPA informs the industries and public on regulatory requirements, develops and implements the Reporting Program, reviews and verifies annual reports, compiles and publishes data, ensures compliance with the requirements, and updates regulations as needed. The GHGRP data also contribute to the U.S. Inventory of Greenhouse Gas Emissions which is prepared by U.S. EPA on behalf of the U.S. Government.
US Mine Safety Health Administration (MSHA)	MSHA has no formal role in the administration of the GHGRP. However, MSHA takes CH_4 and volumetric flow measurements at ventilation shafts on a quarterly basis, and coal mine owner/operators reporting to the GHGRP may use certain measured data from MSHA in their GHGRP reports.
Mine owner/operators	Owner/operators of underground coal mines subject to the rule must register the facility with the GHGRP, take measurements, and submit annual reports. They are also responsible for maintaining records for the required record retention period and make those records available for inspection if required.
CMM/AMM/SMM mitigation project owners	CMM/AMM/SMM mitigation project owners can use the data available to the public to identify CMM, AMM and SMM recovery and use project development opportunities, for example data on volumes and concentrations of CH_4 produced by gas drainage systems. Separately, owners/operators of CMM/AMM/SMM mitigation projects where the mitigation project facility boundary is legally separate from the mine are subject to the stationary combustion reporting requirements of the GHGRP if emissions from combustion exceed the combustion reporting threshold of 25,000 tCO_2e per year. For reference, this equates to combustion of ~470 MMcf (13.3 Mm^3) of pure CH_4 or enough gas to supply a 6 MW power project.[12]
Public	The public (public citizens, print and broadcast media, non-profit organizations, academic organizations, researchers, and others) accesses and analyses the data to better understand CH_4 emissions from the mining sector and to highlight opportunities for emission reduction.

General reporting thresholds including offramps, reporting frequency and reporting system

Not all coal mines are subject to GHGRP reporting requirements. U.S. EPA only requires reporting by operating underground mines that "liberate" at least 36.5 million cubic feet a year (1.034 million cubic metres) of CH_4 a year from mine ventilation shafts and degasification systems. As defined in the regulations, "liberated" means "released from coal and surrounding rock strata during the mining process. This includes both CH_4 emitted from ventilation systems and CH_4 drained from degasification systems" (40 CFR Section 98.6).[13] However, CH_4 liberated does not translate directly to emissions because

[12] Assume 4.2 m^3/m of CH_4 required to produce 1 MW.
[13] Title 40 of the U.S. Code of Federal Regulations Section 98.6 https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl

some quantities of liberated CH_4 may be used or destroyed. Emissions are the net difference between quantities of CH_4 liberated from ventilation and degasification systems less any quantities of CH_4 used or destroyed; essentially the GHGRP uses a mass balance equation to determine emissions.

Operating underground mines liberating CH_4 at volumes less than the reporting threshold, surface mines, and abandoned underground mines do not report to the GHGRP.

Table 5.2 shows the required data elements that must be reported to U.S. EPA.

Table 5.2
Data reporting requirements for the GHGRP

Data Element	Monitoring Points	Monitoring Frequency	Allowed Monitoring Methods			Notes
			MSHA Quarterly Inspection Reports	Manual sampling by mine staff	Continuous Emissions Monitoring	
MSHA ID						Mine Safety & Health Administration ID to check operating status and coal production
Description of degasification system						Manufacturer, capacity, # of wells, surface area, operating hours
CH_4 liberated from ventilation systems (metric tCH_4)	Each exhaust shaft	Quarterly	✓	✓	✓	Based on CH_4% and volumetric flow rate
CH_4 liberated from degasification systems (metric tCH_4)	Each well or centralized monitoring point	Weekly	N/A	✓	✓	Based on CH_4% and volumetric flow rate
CH_4 destroyed on-site/sent off-site (metric tCH_4)	Each destruction device or point of transfer off-site	Weekly	N/A	N/A	✓	Based on CH_4% and volumetric flow rate
Net CH_4 emissions (metric tCH_4)	Mine-wide	Quarterly				Ventilation CH_4 liberated plus Degasification CH_4 liberated less CH_4 destroyed/sent off-site

CO_2 emissions (on-site destruction/no energy recovery) (metric tCO_2)	Mine-wide	Quarterly	[redacted]	Flaring, VAM destruction
CO_2 emissions (on-site destruction/energy recovery) (metric tCO_2)	Mine-wide (subdivided by unit type)	Annual	[redacted]	Reported under Subpart C, combustion emissions

Facilities submit annual monitoring reports to U.S. EPA by 31 March of the year following the reporting year. For example, the deadline for submitting 2020 reports was 31 March 2021. All GHGRP reporting is through a secure online portal – the Electronic Greenhouse Gas Reporting Tool (e-GGRT). Facilities intending to report must register through e-GGRT at https://ghgreporting.epa.gov/ghg/login.do and provide relevant information about the facility including the physical address and an official representative. Depending on the industry sector, GHGRP reporters enter data directly into a web form in e-GGRT or add data to a prescribed MS Excel® workbook and then upload that workbook in e-GGRT. Underground coal mines use an Excel® form, an example of the reporting form can be found at:
https://ccdsupport.com/confluence/display/help/Reporting+Form+Instructions.

Report verification and data publication

The GHGRP is a self-certifying reporting programme with reporters certifying that the data reported is accurate when they officially submit their reports. Although self-certifying, U.S. EPA still reviews all reports to identify potential errors, inconsistencies, and anomalies in the reported data. Where available, U.S. EPA may also check data published in other sources.

The verification stage concludes in July each year, and reported data are published in October on multiple public websites including:

- U.S. EPA's Facility Level Information on Greenhouse Gases Tool (FLIGHT), available at:
  https://ghgdata.epa.gov/ghgp/main.do?site_preference=normal, and
- U.S. EPA's Envirofacts Customized GHG Search, available at:
  https://www.epa.gov/enviro/greenhouse-gas-customized-search.

FLIGHT provides an interactive map where reports for individual facilities can be accessed. Envirofacts presents consolidated industry-wide data for all reporting facilities in downloadable CSV worksheets which are easier to use for data analyses.

Regulatory updates to calculation methods and reporting requirements

U.S. EPA regularly reviews the GHGRP to identify rulemaking changes to address needed technical corrections, to improve data quality, to clarify calculation methods and reporting requirements, and to implement legislative changes. Regulations governing underground coal mines have been updated several times since being first finalised in 2010.

Statistics
Table 5.3 shows the number of underground mines and related CH_4 emissions from 2013 through 2019 as reported by the GHGRP and the U.S. GHG Inventory. Although only about 30% of underground mines report to the GHGRP, those mines account for over 90% of nationwide CH_4 emissions from underground mines.

Table 5.3
Number of underground mines and related CH_4 emissions from 2013 through 2019 as reported by the GHGRP and the U.S. GHG Inventory

Source	Underground mines and emissions						
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Mines reporting to GHGRP	131	130	125	95	79	75	67
Mines included in US GHG Inventory (GHGI)	205	178	220	163	162	164	167
Working US underground mines	395	345	305	253	237	236	226
Total CH_4 emissions GHGRP ($MMTCO_2e$)	41	41	44	39	38	36	34
Total CH_4 emissions GHGI ($MMTCO_2e$)	46	46	45	41	41	39	34.5
GHGRP emissions Coverage	89%	89%	98%	95%	93%	92%	99%
GHGRP facility coverage vs GHGI	64%	73%	57%	58%	49%	46%	40%
GHGRP facility coverage vs all working UG mines	33%	38%	41%	38%	33%	32%	30%

Note: MMT = million tonnes (Mt).
Sources: USDOE EIA, 2019; U.S. EPA, 2019; U.S. EPA 2021.

5.2 U.S. State of California's Cap-and-Trade

The California Cap-and-Trade Program is the largest carbon compliance market in the United States. Although the Program covers a large share of the California economy, ranked fifth in the world by some measures, the coal industry is not a covered industrial sector as there are no operating coal mines in California. However, the California Air Resources Board (CARB), the implementing authority, has adopted a Mine Methane Capture (MMC) Protocol, allowing offsets generated by CMM, AMM and SMM recovery and use projects outside of California to be sold into the Cap-and-Trade market.

Authorizing legislation and regulatory structure
The authorizing legislation for the California Cap-and-Trade Program is Assembly Bill 32 (AB32) passed by the California Legislature in 2006. AB32 established California's 2020 GHG Reduction Targets, required CARB to adopt a scoping plan for achieving the targets, and authorised CARB to include a cap-and-trade programme. AB32 also mandated that policies to reduce GHGs be cost-effective and technologically feasible and not disproportionately impact residents in environmental justice communities.

Follow-on legislation in 2016 set a goal of reducing GHGs by 40% below 2020 levels by 2030. The new legislation also reauthorised the Cap-and-Trade Program and extended the Program to 2030. In doing so, however, the legislation reduced the number of offsets allowed into the market. Compliance entities may use ARB Offset Credits to meet up to

8% of their compliance obligation for emissions through 2020; 4% of their compliance obligation for emissions from 2021-2025; and 6% for emissions from 2026-2030. In addition, the 2016 legislation established a ceiling on the contribution of out-of-state projects. Starting with 2021 emissions, no more than one half of offsets may be sourced from projects outside of California.[14]

In addition to the Cap-and-Trade Program, AB32 also established the Mandatory Reporting of Greenhouse Gas Emissions Program which is applicable to certain sectors in the economy including electricity generators, industrial facilities, fuel suppliers and electricity importers. Implementing regulations were first adopted in 2010 with subsequent amendments adopted about every two years through 2018. Reporting data are published annually and are used to support policy development in the Cap-and-Trade Program and are included in the California GHG Inventory. There are no working or abandoned coal mines in California, and therefore, the industry is not subject to the California Mandatory Reporting Program. Coal mines in other U.S. states are not subject to an emissions cap or the reporting requirements under the CA Cap-and-Trade and Reporting Programs, but they can be part of the Cap-and-Trade Program through generation of offsets into the market.

Role of stakeholders (regulators, facility owners/operators, CMM/AMM/SMM mitigation project owners, the public)

CARB is the regulatory authority and implementing agency responsible for establishing the rules for the Cap-and-Trade Program, approving offset protocols, and managing the Program. The Cap-and-Trade Program is a compliance market with CARB granting emission allowances to facilities in covered sectors. Covered entities may acquire allowances through auction, limited free allocation (for eligible entities), and by trading with other entities in the Program (i.e., the "trade").

CARB also issues ARB Offset Credits to qualifying projects that reduce or sequester GHGs pursuant to six Board-approved Compliance Offset Protocols. Facilities in capped sectors may use offsets to meet a small portion of their cap. CARB has adopted offset protocols for each authorised project type, including the Mine Methane Capture (MMC) protocol, following a public review and comment process.

Officially called the Compliance Offsets Program, the Program is intended to be a cost-containment and compliance flexibility element within the broader Cap-and-Trade Program. Compliance offsets are tradable credits that represent verified GHG emissions reductions from sources not subject to a compliance obligation in the Cap-and-Trade Program.

[14] The requirement is that no more than half of offsets may be sourced from projects that do not provide direct environmental benefits (DEBS) in the state of California. Projects that are located within California are automatically considered to provide DEBS; however, projects located outside the state can also demonstrate to CARB that they provide DEBS by submitting documentation that demonstrates the benefits. Reference: https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/direct-environmental-benefits

With respect to additionality[15], CARB established the offset protocols as performance-based rather than prescriptive protocols meaning that compliance with the protocols confirms additionality without a separate project-by-project review. This is in contrast to a prescriptive programme such as the UNFCCC CDM Executive Board ACM0008 CMM offset methodology (including SMM and AMM) where each project is evaluated independently for additionality.

Before a project can sell offsets into the California Cap-and-Trade Program, the project must apply to and be listed in a CARB-approved independent offset registry. Once the project has met the listing criteria, it submits an Offset Project Data Report listing the quantity of offsets generated. This report is then verified by an independent third-party verifier. After the verification report is reviewed and approved by the registry and posted to the registry website, offset credits are then issued by CARB. One California Compliant Offset (CCO) is equivalent to one metric tonne of carbon dioxide.

The MMC offset protocol was adopted by CARB in April 2014 and became effective on July 1, 2014. It is called the MMC protocol because it includes CH_4 emission reduction projects from trona (i.e., soda ash) mines in addition to coal mines.

Eligible projects can be located at working underground coal and trona mines, abandoned underground coal or trona mines, and working surface coal mines. All end uses effectively qualify for producing offsets including power generation, flaring, and industrial use. The only projects not eligible to generate offsets for the Cap-and-Trade Program are natural gas pipeline sales projects at working underground coal mines. This is because pipeline sales projects are the most common use of drained gas at working U.S. underground mines, thus they are considered to be "business as usual" and not additional. CARB does allow gas pipeline sales projects at abandoned mines to participate unless a gas sales project was started prior to mine closure.

The MMC protocol primarily focuses on quantifying reductions of CH_4 emissions at mines, but accounts for carbon dioxide emissions from combustion of CH_4. The protocol provides eligibility rules, methods to quantify GHG reductions, offset project-monitoring instructions, and procedures for preparing Offset Project Data Reports. Additionally, all offset projects must submit to annual, independent verification by ARB-accredited verification bodies.

Other important stakeholders are the approved project registries, project verifiers, offset project operators (project developers), and purchasers of offsets.

Three project registries are currently approved for listing CARB projects: American Carbon Registry, the Climate Action Reserve and VERRA. The registries are operated by not-for-profit organizations with responsibility for listing and overseeing verification of carbon offset projects. CARB will only issue offset credits for projects listed on these

[15] The offset project results in emission reductions due to actions that are beyond business-as-usual

registries and only after the emission reductions are verified and listed on the registry websites.

Offset verification bodies are independent third-party organizations that have been accredited by CARB to verify offset projects and associated emission reductions. Currently there are 16 approved offset verification bodies. Individual offset verifiers, who work for the verification bodies, must also be accredited by CARB to verify MMC offset projects.

Project developers finance, build and operate mine CH_4 projects that produce offsets. In some instances, these can be the mine owner/operators, but generally they are companies with the expertise to design and build the projects, owning the project outright or sharing ownership with the host mine. Projects participating in the California market thus far have included combined heat and power, power production, flaring, natural gas sales from abandoned mines and VAM destruction. Project developers own the offsets produced by their projects and sell these offsets to compliance buyers as CCOs.

General reporting thresholds including offramps, reporting frequency and reporting system

There are no minimum thresholds for verifying, listing or selling CARB-issued offsets. Projects must be listed with the project registry no later than one year after project commencement, and projects may generate offsets over a crediting period that consists of 10 reporting periods. CARB requires 12-month reporting periods to be verified – with the exception of the first and last reporting periods which can range from 6 to 24 months. The Offset Project Data Report must be submitted within 4 months of the end of the reporting period. The verification must be complete within 11 months of the end of the reporting period. While there are no caps on individual projects, there is a cap on the total number of offsets that can be used in the programme issued and additional restrictions on the total number of offsets with direct environmental benefit to California issued each year as noted earlier.

Report verification and data publication

Emission reductions and compliance with CARB protocols are verified through formal verification audits. Emission reductions are confirmed and restated in the verification statements which are posted to the public websites for the registries. Detailed verification reports are not publicly available.

Statistics[16]

- Number of CARB-approved MMC projects: 24
- Offset Credits Issued: 8,686,882 tCO_2e
- Project with largest offset issuance: 1,902,272 tCO_2e
- Project with smallest offset issuance: 2,236 tCO_2e
- MMC projects listed but not yet verified: 12

[16]Data from the California Cap-and-Trade Program and associated Registries with respect to the Mine Methane Capture Protocol projects as of October 27, 2021 https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program

5.3 United Kingdom

Mine CH_4 emissions monitoring and reporting in the UK was initiated in 1991 by the British Coal Corporation, a nationalised coal producing organization. Weekly spot readings of airflow and CH_4 concentration were made at all upcast shafts during a production shift. Methane discharged from gas drainage plants was also determined. The results were used to calculate a specific emission factor for rearward and forward projections of emissions based on actual or planned coal production. An allowance was made for gas emitted from coal during transport. Contributions from opencast mines and small mines were determined but excluded from the inventory as their emissions only represented about 1% of the total coal mine emissions. The methodology was incorporated in the independent Watt Committee on Energy report on CH_4 emissions (1993) prepared for the UK Government in support of the IPCC process.

After privatisation of the UK coal industry in 1994, the new coal companies reported monitoring results to the Coal Authority – the government organization charged with managing coal assets and inherited liabilities. By that time, all deep mines were equipped with CEMS. The last large, deep coal mine in the UK closed in December 2015. The only significant mine-related emissions thereafter were from abandoned mines.

Abandoned mine methane emissions
With the decline and closure of the coal mining industry during the 1990s there was a high degree of uncertainty on the magnitude and significance of emissions from abandoned coal mines. To gain further clarity and understanding the UK Government commissioned detailed studies that would quantify the true scale of AMM emissions. The initial study resulted in a methodology (Kershaw, 2005a) that involved a groundwater recovery model based on void space calculations and a residual gas reserve model for estimating the residual quantity of gas in unworked coal disturbed by mining. The rising mine water progressively removes gas sources thus, yielding the accessible CH_4 reserves. Methane flow measurements on AMM vents at eight mines and surface flux measurements both showed similar trends against the underlying CH_4 reserves. The combined data sets indicated an emission of 0.74% of the underlying gas reservoir per year. This value was used to back calculate AMM emissions of 52 kt in 1990 to 45 kt in 2004. An extra stage was added to the methodology (Kershaw, 2005b) to take account of high initial emissions from newly closed, gassy mines using a hyperbolic decay curve. In the calculations, it was assumed that AMM mitigation measures (utilization) would reduce emissions from closed mines emitting >0.5kt/year by 70% after year one of closure. Projected AMM emissions ranged from 59kt in 2005 to 16kt in 2050. This methodology might be considered an IPCC Tier 2/Tier 3 hybrid.

Following the cessation of large-scale deep coal mining in the UK, mine water recovery is progressing or complete in all the coalfield areas of the UK resulting in the reduction in the emissions from abandoned mines.

Reporting
Estimated atmospheric emissions of AMM were reported by the UK Government Department of Energy and Climate Change (now amalgamated into the Department for

Business, Energy and Industrial Strategy – BEIS) to the UK National Atmospheric Emission Inventory (NAEI), which includes the UK Greenhouse Gas Inventory, and AMM emissions represented about 1.5% of UK anthropogenic CH_4 emissions and 0.17% of the total UK GHG emissions in 2018. The AMM methodology is complex and uncertainties are in the range ±20 to ±40%. There was no formal verification process other than comparison of different approaches to estimation of emissions and also a third-party review and update (Fernando, 2011).

The Coal Authority is currently commissioning a further review of CH_4 emissions and the methodology to gain an updated position and current figures to be reported.

The Single National Entity responsible for submitting the UK's GHG information to the UNFCCC is the government department for BEIS. Other bodies and government departments are involved in data collection. From 1 April 2019, large UK companies were required by the UK government to report publicly on their UK energy use and carbon emissions within their Directors' Report. However, no coal mining companies remained that would qualify. (Qualifying companies are those that exceed at least two of the following three thresholds in the preceding financial year: £36m annual turnover; £18m balance sheet total; 250 employees).

Emissions trading

The UK established Europe's first multi-sector emissions trading system in 2001, introducing the concept of carbon pricing to incentivise carbon emission reductions. Although a voluntary scheme, direct participants could take on obligatory emission targets in exchange for government subsidies. It served as a pilot for the EU Emissions Trading System (EU ETS), into which it later merged. Drained gas utilisation and flaring projects were developed at some working mines under the UK pilot scheme. The emission reductions were ultimately captured in the UK inventory.

A new UK Emissions Trading System (UK ETS) replaced the UK's participation in the EU ETS on 1 January 2021. The last deep mine closure having receded into time, the scale of AMM emissions is now only of importance as a fugitive emission hazard.

Mitigation

Mitigation of CMM emissions at working mines was achieved mainly through use of drained CMM for power generation and direct thermal use. Flaring was practiced for a short while under a voluntary emissions reduction scheme but in the absence of a long-term financing mechanism was discontinued. VAM destruction was demonstrated but no commercial project implemented.

The first recorded use of AMM in the UK was in the 1950s when gas was extracted from a closed mine to feed the hot water boilers at a neighbouring working mine. Full expansion of AMM exploitation was started in 1994 by Coalgas (UK) Ltd, later to become Alkane Energy, now acquired by Infinis Energy. Subsequently, other companies entered the market. The AMM developers campaigned unsuccessfully for their projects to be classified as "renewable energy," as in Germany, to attract similar benefits. AMM utilisation schemes were developed at a number of sites following colliery closure, mainly for power generation typically in the range of 10-15 MW_e. A few projects provided medium quality gas for direct use. Alkane Energy operated the largest portfolio of AMM and, at the time of being acquired by Infinis Energy in 2017, had 32 sites with a total of 160 MWe capacity. At some sites methane availability has reduced due to exhaustion and mine flooding, with some power generation being converted to natural gas to provide profitable short-term power on peak demand to the grid. Today, Alkane's successor, Infinis, continues to operate 15 sites with a total capacity of 44 MW_e reducing more than 40,000 tonnes of CH_4 per year (+1 million tonnes CO_2 equivalent).[17]

AMM exploration and development is regulated under the oil and gas licensing regime managed by the Oil and Gas Authority.

5.4 Australia's National Greenhouse and Energy Reporting (NGER)

The National Greenhouse and Energy Reporting (NGER) Act of 2007 requires coal mines and other industry sectors in Australia to report their annual fugitive emissions. This Act established a national framework for reporting and disseminating company-level greenhouse gas emissions, energy production and energy consumption. The NGER Scheme is administered by Australia's Clean Energy Regulator. Coal sector companies have reported since 2009, and companies were required to use direct monitoring of emissions at underground mines since 2011. In addition to the reporting scheme, the NGER Act was amended in 2014 to establish a "Safeguard Mechanism", that requires Australia's largest emitters to keep their net emissions below a baseline, or emissions limit.

The NGER Scheme aims to collect emissions information to:

- "inform Australian Government policy and the public
- meet Australia's international reporting obligations and measure progress against Australia's international climate change commitments
- assist Australian Government, state and territory government programmes and activities
- avoid duplication of similar reporting requirements in the States and Territories."[18]

Authorizing legislation and regulatory structure

The NGER Act is the head Act establishing Australia's GHG reporting scheme, and several regulatory instruments were developed under this act: the National Greenhouse and Energy Reporting Regulations 2008 provide further detail on reporting obligations and Scheme administration, while the National Greenhouse and Energy Reporting (Measurement) Determination (2008)[19] describes methods for estimating greenhouse

[17] https://www.infinis.com/generation-activities/captured-mineral-methane

[18] The Government of Australia, Clean Energy Regulator. 2021. http://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data

[19] Australian Government. Federal Register of Legislation. https://www.legislation.gov.au/Details/F2020C00600

gas emissions, energy production and energy consumption[20] (NGER, 2021). In 2015, the National Greenhouse and Energy Reporting (Safeguard Mechanism) Rule 2015 established compliance rules and procedures for administering the Safeguard Mechanism, which set emissions limits, or baselines, for large facilities, whose scope 1[21] emissions exceed 100,000 tCO_2e per year[22] (NGER, 2021).

The NGER Act helped streamline reporting requirements at the national level, since prior to NGER companies reported similar information for different agencies and different territories. Coal mining companies still report safety-related information to Territories, who have the responsibility and the authority to manage coal mine safety.

General reporting thresholds including offramps, reporting frequency and reporting system

All types of coal mines – working underground and surface as well as abandoned underground mines – are required to report emissions to the Clean Energy Regulator if their emissions, energy production or consumption go above established thresholds. There are two types of thresholds that determine which companies have the reporting obligation: a facility threshold and a corporate group threshold. As of 2021, facility thresholds were:

- "25 kt or more of greenhouse gases (CO_2e) (scope 1 and scope 2[23] emissions)
- production of 100 TJ or more of energy, or
- consumption of 100 TJ or more of energy."

Similarly, corporate group thresholds were:

- 50 kt or more of greenhouse gases (CO_2e) (scope 1 and scope 2 emissions)
- production of 200 TJ or more of energy, or
- consumption of 200 TJ or more of energy" (NGER, 2021)[24].

If facilities do not meet reporting thresholds, companies might still have to report if they meet corporate thresholds. In practice, these thresholds capture all coal mining companies.

Australia's Measurement Determination lays out four methods for estimating emissions:

- Method 1 is the simplest method, in which emissions are estimated by reference to activity data and specific emission factors.

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[20] The Government of Australia, Clean Energy Regulator. 2020. Legislation. http://www.cleanenergyregulator.gov.au/NGER/Legislation

[21] Scope 1 emissions implies direct emissions from fugitive sources and emissions from fuel combustion, waste disposal and industrial process.

[22] Australian Government. 2020. The safeguard mechanism. http://www.cleanenergyregulator.gov.au/NGER/The-safeguard-mechanism

[23] Scope 2 emissions are emissions released as a direct result of activities use generate electricity, heating, cooling or steam by the facility but that are not part of the facility.

[24] Australian Government. 2020. Facility and Corporate Group Thresholds. http://www.cleanenergyregulator.gov.au/NGER/Reporting-cycle/Assess-your-obligations/Reporting-thresholds

- Method 2 is a facility-specific method that relies on gas modeling. Corporations can take additional sampling and measurements using Australian or international standards to provide more accurate estimates of emissions at the facility level. For example, such standards are published by the Australian Coal Association Research Program (ACARP).
- Method 3 is similar to Method 2, except it requires use an appropriate standard for gas sampling that are specified in NGER Measurement Determinations, rather than rely on standards that are published by the Australian Coal Association Research Program (ACARP).
- Method 4 involves direct monitoring of emission systems, either continuously or periodically, and it the most data intensive process.

Mining method and type determine the method choices that are available for mining companies. For example, companies mining underground must use method 4 while having a choice of using CEMs data or periodically measuring both their CH_4 and carbon dioxide emissions at reporting schedules they must propose based on variability in operations. Abandoned mines that are no longer venting must report using emission decay curves for gassy and non-gassy mines (depending on water intrusion factors). Open cut mines have a choice of using method 1, 2 or 3 for estimating their CH_4 emissions. If method 2 or 3 are used then open cut mines must also report carbon dioxide. In 2019, 49% of energy sector CH_4 emissions were measured using method 4, while 12% emissions were estimated used methods 2 and 3 (Australia's National Inventory Report 2019).

The reporting year starts on July 1 and finishes on 30 June, consistent with Australian financial years, and reports are due October 31st. All reporters must submit their reports through the Emissions and Energy Reporting System: http://www.cleanenergyregulator.gov.au/OSR/EERS/The-Emissions-and-Energy-Reporting-System.

A company that would be liable to submit NGERS reports for a facility may apply to the Regulator to transfer its reporting responsibilities to another company which operates the facility on its behalf.

Companies must typically report the data listed in **Table 5.4** under NGER:

Table 5.4
Data reporting requirements under NGER

Activity	Typical significant coal mine NGER data	Other required coal mine NGER data
Fugitive emissions from underground mines	• Gas flow and gas concentration from mine return ventilation. • Gas flow, gas concentration, gas pressure for gas drainage emissions and flaring (for auditing purposes). • Emissions from decommissioned underground mines.	• Gas temperature, pressure. • Post-mining emissions from gassy mines.
Fugitive emissions from open cut mines	• Run-of-mine (ROM) coal production, • Gas in extracted gas bearing strata, based on in-situ gas sampling and gas modelling (if using method 2 or 3).	
Energy production	• Saleable coal production.	• Gas captured for on-site combustion, flaring, or gas transferred outside the facility (if injected into pipeline). • On-site electricity generation (if exceeding reporting threshold).
Fuel combustion / Energy consumption and emissions	• Diesel consumption in heavy mining equipment. • Gas captured for on-site combustion or flaring (if injected into pipeline). • Purchased electricity consumption.	• Other fuel combustion, e.g., diesel or petrol for light vehicles. • Oils and greases consumed. • Non-combusted diesel use, e.g., use as flocculent or in explosives.
Other data or emissions	• Uncertainty assessment. • Raw coal production (as a Matter to be identified (MBTI)), reported as ROM coal.	• Emissions from sulphur hexafluoride (SF_6) (where applicable).

Source: Australian Government, Clean Energy Regulator. "Estimating emissions and energy from coal mining guideline". 2021.
http://www.cleanenergyregulator.gov.au/DocumentAssets/Documents/Estimating%20emissions%20and%20energy%20from%20coal%20mining%20guideline.pdf

The NGER scheme does not cover emissions from the agriculture, land use, land use change, forestry, private vehicle transport and residential sectors.

Notably, the Australian Government provides substantial video training materials on the reporting scheme, methodologies, as well as the portal itself. All videos can be accessed here:
http://www.cleanenergyregulator.gov.au/OSR/EERS/Tools-to-assist-you/Training-videos.

Report verification and data publication

The Clean Energy Regulator maintains a register of auditors[25] who are engaged to verify that NGER's reporting obligations have been met. Notably, auditors are provided with instructions, guidebook and templates they can use in conducting audits.

Verified data are published in aggregated format by the Clean Energy Regulator. Corporations can apply to have all or part of their reported GHG emissions and energy

[25] http://cleanenergyregulator.gov.au/Infohub/Audits/register-of-auditors#:~:text=The%20Register%20of%20Greenhouse%20and%20Energy%20Auditors%20is,must%20demonstrate%20that%20they%20satisfy%20the%20eligibility%20requirements

production and consumption totals withheld from publication. The Australian Government makes the following information on coal sector emissions available[26]:

- Corporate emissions and energy data: Annual scope 1 emissions, annual scope 2 emissions in CO_2e for corporations, and net energy consumed.
- National Greenhouse and Energy Register: A list of corporations that registered or deregistered to report in a given reporting year as well as a list of largest emitters that fall under the Safeguard Mechanism.
- Safeguard facility reported emissions.[27]

The NGER Scheme was designed to be compatible with IPCC guidelines for inventory submissions and aids in compiling such reports. The 2019 annual inventory report is available at:
https://www.industry.gov.au/data-and-publications/national-greenhouse-accounts-2019.
The latest data can be found here: https://ageis.climatechange.gov.au/.

Statistics

- The total fugitive coal sector CH_4 emissions in the latest reporting year (2019) are shown in **Table 5.5** in Gigagrams (=Kt)
- Number of coal mining industry reporters under NGER: 58 company reporters
- Number of underground mines: 41
- Number of coal mining industry reporters under the safeguard mechanism: approximately 60 facilities

Table 5.5
Fugitive coal sector CH_4 emissions totals in 2019 (Gg CO_2e using AR5 GWPs)

Coal Mining	25,149.36
Underground Mines	17,653.81
Abandoned underground mines	979.8
Mining Activities	15,526.34
Post-Mining Activities	1,147.68
Surface Mining	7,495.55

Source: Australian Government. 2021. Available at: https://ageis.climatechange.gov.au/

5.5 Coal Emissions in China's National Emission Reporting System

Information on methane emissions from China's mines has been gathered at provincial level for many years as all coal mines in China were required to report their CH_4 emissions to the former State Administration of Coal Mine Safety (SACMS), now part of the Ministry of Emergency Management, for safety evaluations. However, reporting of emission factors and production was not mandatory (Sheng et al., 2019).

[26] See here for links to the datasets below:
http://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data/Data-highlights/2019-20-published-data-highlights
[27] This dataset can be found here:
http://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data/safeguard-facility-reported-emissions/safeguard-facility-emissions-2019%E2%80%9320

The SACMS database, 2011, covered 10,963 coal mines in 26 coal-producing provinces in mainland China. Each coal mine measured its emissions by continuously monitoring its ventilation and degasification systems during its annual safety evaluation (2–3 months). A total emission rate of 53,000 m^3/m and an overall capture rate of 15,000 m^3/m was obtained for 2011.

Gao et al. (2020) reviewed bottom-up inventories for China and noted that more work needs to be done to improve the accuracy of the results due to the differences in the range and variability of emission factors applied to underground coal mines. As coal mines are a major CH_4 emission source in China, a clear need has been identified for more reliable CMM inventories, systematic application of CH_4 mitigation measures, and inclusion of emissions from abandoned coal mines.

After a gestation period of some ten years, China's national ETS officially became operational in 2021 but the current phase only covers the power sector. The Government considers that its ETS can help the country to achieve the dual carbon goals of peaking emissions by 2030 and carbon neutrality by 2060. MRV will be an essential tool in pursuing these ambitious targets.

A declaration by China and the United States at COP26 in Glasgow, indicates that both countries are prepared to work together to strengthen CH_4 emissions measurement and control:

The two countries intend to cooperate to enhance the measurement of methane emissions; to exchange information on their respective policies and programmes for strengthening management and control of methane; and to foster joint research into methane emission reduction challenges and solutions.[28]

5.6 Kazakhstan

Kazakhstan has several policy elements in place to monitor, verify and report CH_4 emissions from coal mining. The Environmental Code requires monitoring CH_4 emissions and sets fines for air pollution, but CMM, AMM and SMM are not included in the national ETS established in 2013. Kazakhstan reports CH_4 emissions from coal mines to the UNFCCC, which are calculated using a combination of Tier 1, 2 and 3 approaches.

Authorizing legislation and regulatory structure

Coal mining companies have monitored CH_4 emissions for safety reasons since the Soviet times. More recently, Kazakhstan further developed legislation on the safety rules system in the coal industry. Several laws provide the foundation for this system. They include laws "On Industrial Safety at Hazardous Production Facilities" (2002), "On Technical Regulation" (2004), and "On State Control and Oversight in the Republic of Kazakhstan" (2011).

The *Technical Regulation* defines key principles for CH_4 safety during coal production. These rules are further refined in the *Industrial Safety Rules*. This document obliges mine

[28] U.S. Department of State, 2021. U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s - United States Department of State

operators to develop manuals for each underground mine to identify safety rules and procedures specifically designed for that mine. These manuals should contain information about the composition of the mine air, rates of CH_4 emissions, parameters of mine ventilation, and detailed procedures related to various emergencies.

Kazakhstan developed an emission trading system for CO_2 in 2013. The Ministry of Energy, the Ministry of Ecology, Geology and Natural Resources and Zhasyl Damu are involved in the implementation of the Kazakhstan ETS. Kazakhstan's ETS covers six sectors, including mining. The National Allocation Plan sets caps for annual emissions from participating installations, including 24 facilities in mining[29]. In January 2021, Kazakhstan changed the allocation method to use a benchmark approach starting July 2021. However, CH_4 is not included in the emissions cap as CH_4 emission reductions should be achieved through the implementation of internal emission reduction projects.

Kazakhstan, as an Annex I country, started reporting its GHG emissions to the UNFCCC in 2009. Several institutions were involved in the preparation of international reporting, including the Ministry of Environment Protection (2009-2014) and the Ministry of Energy (2014-2019). Since 2019, the Ministry of Ecology, Geology and Natural Resources prepares national reports on GHG emissions. Zhasyl Damu, a structural unit of the Ministry of Ecology, Geology and Natural Resources, has been collecting and analyzing data and developing international reporting since 2010.

General monitoring requirements and methane reporting rules

Under the national emission reporting programme, each mine should have a register of CH_4 measurements and emissions accounting. This register has several sections, including data on CH_4 concentrations, emissions accounting, elevated CO_2 concentrations, and CH_4 outbursts.

All coal mines are divided into five categories by relative CH_4 emissions measured in cubic metres per tonne of mined coal. **Table 5.6** shows several measures for CH_4 monitoring and reporting for coal mines by CH_4 category. Mines should record data on CH_4 concentrations daily at the beginning and end of each shift. Additionally, mines should report any incidents with CH_4 outbursts. For safety reasons, some mines conduct continuous monitoring of CMM concentrations in key areas of the mines (e.g., mine face, CH_4 drainage, and ventilation systems). Where mines are equipped with CH_4 measurement devices for continuous monitoring, the mine should record measurements from these devices in the register of CH_4 measurements and emissions accounting.

[29] Government of Kazakhstan, 2021. National plan for the allocation of quotas for greenhouse gas emissions for 2021. Available at https://adilet.zan.kz/rus/docs/P2100000006. (In Russian).

Table 5.6

Methane monitoring and reporting for coal mines in Kazakhstan by category

Mine category per CH_4 emissions	Relative CH_4 emissions, m^3/t	Frequency of CH_4 concentration checks (when continuous monitoring is not available)	Air compositi on checks	Frequency of ventilation system check by independent organization
I	Less than 5	Two times per 6-hour shift	Monthly	3 years
II	5 -10	Two times per 6-hour shift	Monthly	3 years
III	10-15	Three times per 6-hour shift	Twice a month	2 years
Over category	Over 15	Three times per 6-hour shift	Three times a month	2 years
Mines, dangerous for outbursts	CH_4 and coal dust outbursts	Three times per 6-hour shift	Three times a month	2 years

Source: Compiled from "The industrial safety rules for hazardous production facilities at coal mines"

Underground coal mines report their CH_4 emissions to the Ministry of Industry and Infrastructural Development and any CH_4-related accidents to the Ministry for Emergencies. These reports have not been used to prepare national GHG reports. As a result, there is no verification of reported coal mine CH_4 emissions. Mines report coal production data to the Committee for Statistics of the Ministry of National Economy and the Ministry of Energy.

Calculation methods

To calculate emissions from coal mines for UNFCCC reporting, Zhasyl Damu uses data on coal production and emissions factors[30] by coal basin or determined from individual mines provided by the Ministry of Energy.

To calculate CH_4 emissions from coal mines before 2017, the country used the implied emissions factor (IEF) for underground coal mines in the range of 24-34 kg of CH_4 per tonne of coal mined (kg/t) and revised it to 16 kg/t in recent years. Kazakhstan used very high IEF values for surface mines (7-8 kg/t), which were the highest values of all reporting Parties, well above the IPCC default range (0.2–1.34 kg/t)[31]. In the 2021 submissions of the national inventory data in the common reporting format (CRF) to UNFCCC, Kazakhstan updated the emission factor for surface mines to 0.87 kg/t and started reporting emissions from abandoned mines (with an IEF of 0.25 kg/t).

[30] Government of Kazakhstan, 2010. Guidelines for calculating greenhouse gas emissions into the atmosphere for coal mining and processing enterprises from underground coal mining. Available at https://www.egfntd.kz/rus/page/ME_RK.html (In Russian).

[31] UNFCCC, 2014. Report of the individual review of the inventory submission of Kazakhstan submitted in 2012. Available at https://unfccc.int/resource/docs/2013/arr/kaz.pdf

6. MRV programme design considerations

Key messages

- The aim of MRV, applied to coal mine-related CH_4 emissions, is to quantify the scale of emissions and provide policy makers and stakeholders with a means of identifying mitigation opportunities and determining their effectiveness.
- This chapter provides guidance to decisionmakers charged with developing a national MRV scheme on key design elements for a national GHG reporting and monitoring system.

There is no perfect system and decisionmakers must consider a range of factors to determine the most appropriate and effective MRV design for a particular jurisdiction, including policy priorities, economic impacts, cultural impacts, logistics and other factors. Overall, the most important considerations include:

- The policy framework for the MRV programme, such as legislative, regulatory and administrative approaches
- Roles for relevant stakeholders
- Sources of coal sector emissions and options for monitoring emissions from those sources
- CH_4 monitoring and verification of measurements at the facility level
- Determining target subsectors within the coal sector (working, abandoned and surface mines)
- Reporting thresholds (facility type or size, emission size)
- Quantification methods (aligned with international standards)
- Programme structure (reporting frequency, platform, recordkeeping, publication)

To start, the MRV system must be developed within an appropriate legal, regulatory and administrative framework (**Table 6.1**). Policy objectives guide what type of MRV programme is preferred and what type of mandate and authorities are required to implement the programme. Regulatory structure depends on the governance system in place in a given country.

Table 6.1

Legislative, regulatory and administrative framework for establishing an MRV programme

Aspects of the policy framework	Approaches	Key considerations regarding approaches
Policy objectives	Define policy objectives for the MRV programme	• Provides detailed emission data for GHG inventory • Supports understanding of emission sources to support mitigation activities
		• Ensures compliance with GHG emission caps • Supports compliance or voluntary emissions trading programmes • Support emission reduction commitments in Nationally Determined Contributions (NDCs) • Ensures transparency
Legal authority	Adopt new or amend existing legislation	• Requires political action • Provides overarching authority with minimal detail • Is most effective if there is understanding of the legislative process and timelines and engagement of relevant stakeholders
	Develop clarifying regulation	• Requires administrative action by a relevant authority, usually a government agency, to develop and implement regulation • Establishes technical and administrative requirements for authorization of activities • Requires development of detailed standards and requirements for MRV • Requires development of policies and procedures for non-compliance and remedies • Is most effective if there is understanding of the legislative process and timelines and engagement of relevant stakeholders
	Issue an executive mandate	• Refers to an executive action without formal legislative or regulatory development (may not have same authority as legislation and regulation in certain jurisdictions) • Establishes technical and administrative requirements for authorization of activities • Requires development of detailed standards and requirements for MRV • Requires development of policies and procedures for non-compliance and remedies
	Publish guidance	• Establishes documents, tools, training or other materials and programmes that are usually not legally binding • Supplements legislation, regulation, and executive mandates • Provides support to regulated community and public to improve implementation and compliance with legal and regulatory requirements
Regulatory infrastructure	Define primary implementing authority	• Authorises the principal ministry, agency, department or other implementing unit to develop and implement the programme • Ensures resources are sufficient to secure and retain staff, maintain an operating budget and provide infrastructure to effectively implement and operate the MRV programme
	Establish procedures for reporting data	• Defines the format(s) for reporting data • Establishes administrative procedures for retention, protection and release of confidential data • Establishes policies for determining whether reported data will be public or confidential • Requires development of policies and processes for making reported non-confidential data available to the public

	Consider establishing incentives and compliance programmes	• Includes identifying barriers to compliance • Develops and implements a plan to remove barriers or include incentives to comply • Establishes accessible and effective compliance assistance with regular on-line and in-person training, on-line resources, Help Desk, etc. • Establishes penalties or fees for non-compliance
	Plan for continual improvement	• Requires planning and instituting processes for continual improvement • Seeks input from all stakeholders • Performs self-evaluations or seeks third-party evaluation • Plans for regulatory updates as needed • Refines and improves guidance, tools and other supporting mechanisms • Conducts exchanges with other MRV programmes to learn and refine best practices • Provide *ab initio* and refresher training on changes to programme requirements, measurement protocols and practices and reporting

The MRV system is most effective when it recognises and defines the roles of the various stakeholders, such as the public, government, environmental regulators, facility owners, independent verifiers, and mitigation project developers and investors, as summarised in **Table 6.2.**

Table 6.2
Roles of stakeholders in an MRV programme

Type of stakeholder	Roles of stakeholders in an MRV programme
Regulatory agency	• Interpret legislative mandate or decree and implement regulatory programme • Draft regulatory requirements for MRV • Receive, review, compile, verify and publish data • Ensure compliance with regulations and enforcement for non-compliance • Design and deliver compliance assistance support • Report to legislative or executive authority • Ensure that the reporting burden is commensurate with the value the MRV data offers
Agency reporting national GHG emissions internationally	• Compile data annually in compliance with international standards • Develop and improve methodologies for nationwide emission estimates • Prepare and publish GHG inventory • Submit inventory to UNFCCC
Facility owner/operators	• Conduct monitoring and reporting to comply with all legal requirements • Provide access to supporting data and records, including on-site inspections by regulatory authorities or authorised parties • Comply with any penalties, fees or other action for non-compliance • Ensure mine operations and any GHG mitigation projects comply with mine safety and other relevant regulatory requirements • Publish data in company reports, websites or other media to highlight GHG emissions, MRV compliance and GHG mitigation actions • Participate in legislative or regulatory processes by providing comment on draft legislation and proposed regulations
CMM/AMM/SMM project owner/operators	• Use publicly available MRV data to identify drained gas, VAM, AMM and SMM emission reduction project opportunities • Design, finance, build, commission and operate drained gas, VAM, AMM, SMM mitigation projects • Cooperate with the host mine, mineral rights owner(s), landowner(s) or other counterparties to install and operate the project

	• Comply with all regulatory requirements including requirements for: GHG management and reporting, air quality, water quality, waste management, other environmental, construction, operating and mine safety • Monitor and report GHG emissions and emission reductions specific to the mitigation project(s), possibly in cooperation with the host mine • Secure services of verifying body if verification of emission reductions is required • Publish data in company reports, websites or other media to highlight GHG emissions, MRV compliance and GHG mitigation actions • Participate in legislative or regulatory processes by providing comment on draft legislation and proposed regulations
Third-party verifiers	• Review and independently verify emission and emission reduction reports for regulatory compliance or emissions trading schemes • Participate in required training and certification to be authorized verifiers
Offset project registries	• Adopt protocols for CMM, AMM and SMM projects to register emission reductions from mitigation projects • Provide public listing of CMM, AMM and SMM projects that are proposing to comply with the protocols • Review and approve or disapprove verification reports for emission reductions from these projects
Public GHG registries	• List projects, emissions, and emission reductions • Provide platform for aggregating and publishing submitted and verified GHG data
The public	• Participate in legislative or regulatory processes by providing public comment on draft legislation and proposed regulations • Provide public comment on project registry protocols, project registry listings and verification reports • Track and interpret data published MRV data and prepare analyses for private or public consumption

When designing the MRV scheme, it is important to consider the method of coal production and emission sources (the CMM, AMM or SMM), and determine the relevant monitoring approach for each source. **Table 6.3** lists the monitoring options and identifies the best practice method.

Table 6.3
Identify the CMM, AMM and SMM sources and corresponding monitoring options

CH_4 source	Monitoring approaches under MRV programmes	Best option for national MRV based on current science and practice
Working coal mine	1. Emission factor applied to coal production at national scale 2. Emission factor applied to coal production a regional or mine-specific scale and validated with local measurements 3. Facility level measurements of VAM and gas drainage (if present) a) Using handheld equipment to make periodic spot measurements b) Continuous emissions monitoring (monitoring equipment and measurement on-site, with data transmitted and analysed at remote location) 4. Remote satellite or aerial survey to provide spot readings subject to evaluation and acceptance	3b
Surface mine	1. Emission factor applied to coal production at the national level 2. Emission factor applied to coal production at the regional or mine-specific level and validated with local seam gas content measurements	2

	3. Ground-based open path infrared monitoring, or similar, providing spot measurements. 4. Potential for use of remote satellite or aerial survey of specific location and at specific times subject to acceptance and validation of the technology	
Abandoned mine	1. Generic decline curve starting from total gas flow at closure 2. Regionally determined decline curve starting from gas flow at closure 3. Regionally determined decline curve using mine-specific vent flow measurements, starting from gas flow at closure 4. Regionally determined decline curve using vent flow measurements, starting from gas flow at closure with allowance for flooding rate	4
Post-mining	1. Emission factor established through residual gas content of coal after leaving the mine, applied to coal production that shows emissions during storage, processing and transport	1

Effective policymaking and mitigation action require good data. Therefore, a more accurate and complete the MRV scheme will provide a more precise basis for action and measurable outcomes. The preferred approach to MRV, then, is facility-level measurement, where feasible, as it provides more precise data that can later be aggregated to other levels, depending on the need. This approach in practice is feasible for working underground mines (see **Table 6.4Table**). Alternatively, hybrid methods are used for monitoring emissions from abandoned mines, which generally involve a combination of direct measurements and evaluation based on regional decline trends. Similarly, verification rules should ideally be designed to include all aspects of facility-level measurements.

Table 6.4
Managing facility-level measurements

Facility monitoring and reporting activities			Verification
Measurement	Frequency of measurements	Periodic spot measurements can be from daily to annual depending on CH_4 flow variability Continuous (typically 1-10 minutes sampling rate) preferred where feasible	Check for consistency with the monitoring scheme
	Data processing	Data pre-processing and statistical analysis based on user specification	Check that the agreed data analysis protocols have been followed
		Out of range/failed state data treatment	
		Missing data treatment	
	Management of raw data	Remote transmission and storage	Ensure data backup and security are in place
		On-board storage	
	Installation and operation of measurement instrument	Position sensitivity	Inspect installation of measurement instruments
		All-weather proofing	
		Parameter sample conditioning	
		Parameter measurement frequency	
		Maintenance	
	Proper operation of the sensors	Calibration	Check calibration dates and certificates of sensor
		Accuracy	Ensure that the measurement system compliant with standard
		Performance limits	
		Failure characteristics	
	Measurement of required variables	Monitor each required parameter	Ensure that the required parameters are monitored

Results	Calculations	Calculate and organise results to match required output specification	Check compliance with the monitoring methodology
		Combine relevant parameters to produce required output	Check formulae in the algorithm
	Documentation	Compile all data, supporting information, calculations and results in safe storage with backup for an agreed period of time	Facility for retrospective checks
Reporting	Record results in the established reporting system	Note any issues	Examine report for completeness and correctness (see Chapter 3.3)

The overall MRV programme structure must be consistent with and support national policy objectives relating to coal mine emissions. To ensure acceptance of the programme among reporters, the overall programme requirements should avoid unnecessary complexity and consider the practicalities of workload on facilities for monitoring and reporting, without sacrificing accuracy (**Tables 6.5** and **6.6**). Thus, it might be helpful to prioritise reporters by considering the largest share of CMM, AMM and SMM emissions and those sources of emissions that can be ultimately mitigated. Similarly, it might be helpful to balance between the reporting burden and the level of detail necessary, posing the following questions:

- Is there a balance to strike between the burden to reporters and the level of detail sufficient for the relevant authority and the public?
- Do facilities have the technical capacity and experience to correctly monitor, measure and report data?
- Will the cost of the monitoring and reporting requirements be commensurate with the benefits derived from the reported data?

Considering these points can help establish thresholds for reporting, as described in **Table 6.5**.

Table 6.5
Options for choosing reporting thresholds in an MRV programme

Reporting threshold type	Options	Considerations
Reporting thresholds by facility type	CMM	• Largest source of mine CH_4 emissions and therefore should be first priority for reductions where gassy operating mines continue to operate • Operating facilities with staff are in place to perform monitoring and reporting • Monitoring and measurement already performed for mine safety • Should be able to measure using spot measurements with handheld instruments or continuous monitoring • Two emission pathways exist, namely, mine ventilation fans and gas drainage • CMM mitigation projects are likely using continuous monitoring
	AMM	• Growing source of mine CH_4 emissions in some countries • Should be included in GHG inventory for countries with considerable AMM emissions using decline curves • Mandated MRV for owner/operators of abandoned mines more difficult than working because responsible party may be the landowner or difficult to identify • MRV should apply to AMM emission reduction projects; emission reductions claimed for specific time periods should be closely scrutinised

	SMM	• Limited to certain basins • Emission factors are sufficient as monitoring method • Should be included in GHG inventory • Mandated MRV for owner/operators of surface mines may be appropriate where surface mines contribute large share of mine CH_4 emissions • MRV should apply to SMM emission reduction projects
Reporting threshold by emission size	Absolute emissions threshold	• If using a reporting threshold, most appropriate threshold since it is directly related to GHG emissions • Methane liberation or CH_4 emissions threshold (annual, daily, etc.) • Share of regional or nationwide emissions threshold
	Specific emissions threshold	• Minimum emission in m^3 of CH_4 per tonne of coal mined • More likely to capture larger share of emissions than coal production, gas content and coal rank
Reporting threshold by facility size	Coal production threshold	• Annual run-of-mine coal production • Annual saleable coal production ▪ Not recommended unless there is a direct correlation between annual production and annual emissions for entire industry
Other types of reporting thresholds	Coal rank and market	• Only facilities mining certain ranks of coal are required to report • May eliminate some mines such as brown coal mines (sub-bituminous and lignite coal mines) • Not recommended because there are known instances of gassy underground brown coal mines
	Gas content threshold	• Minimum average gas content of in-situ coal ▪ Not recommended since factors in addition to gas content impact facility emissions

MRV programme design should also include structural elements described in **Table 6.6**, that cover reporting frequency, reporting platform, verification, recordkeeping and data publication options.

Table 6.6
Overall MRV programme structure

Structural elements of an MRV programme	Options	Considerations
Reporting frequency	Annual	• Easier to administer for relevant authority • Lower reporting burden for reporters
	Same as monitoring frequency	• Except for continuous monitoring, could be very burdensome for reporters, especially daily, weekly or even monthly reporting • Potentially significant cost to the relevant authority to receive and manage the data and to the reporter to compile and submit the data • Unlikely to provide additional benefit for the relevant authority or the public
Reporting platform	Online	• Relevant authority creates and manages an online portal for reporting data • Can use web-form where data entered in cells or can accept reports in some other format such as MS Word, MS Excel, .pdf, .jpeg, etc. • Facilitates quick submission and review of reports, and compilation and parsing of data • Immediate creation of electronic records • High initial start-up costs, but could be more cost-effective in long run
	Paper	• Paper submissions • Easy and low cost at start • Higher cost in management of paper submissions and recordkeeping • Requires digitization or data entry to compile data – very expensive
	Automated	• Direct delivery of data to relevant authority in real-time • Only available to facilities using continuous monitoring

Reporting, report verification and recordkeeping	Data to report	Depends on the jurisdiction and programme objectives, but at a minimum, reporters should include: • Date of report • Facility name, address, contact • Owner/operator • Total CH_4 emissions • CH_4 emissions from mine ventilation systems (working underground mines) • CH_4 emissions from mine gas drainage systems (working underground mines) • CH_4 emissions from abandoned mines (if considered relevant) • CH_4 emissions from surface mines (if considered relevant) • CH_4 emission reductions • CO_2 emissions from use of CMM/AMM/SMM
	Report verification	• Third-party verification • Self-certification • Verification of reports by the relevant authority using automated checks and manual checks • Comparison to external data sources
	Recordkeeping & records retention	• Underlying data for reports should be kept on-site or in a data repository for a period of time following submission by the reporter, for example 3, 5 or 10 years. • Data should be made available upon request or site inspection for the relevant authority • Provide secure, independent data storage for reported data
Data publication	Portal for data publication	• Online data publication, if available, should be easy to access for the public • Release of data upon request
	Data summaries	• MRV programmes can benefit immensely from easily accessible websites summarizing data highlights
	Public versus confidential data	• Make public the following: emissions data, data inputs to emissions equations, and other relevant data including the sources of emissions, the type of mining, coal production • Establish plan for securing and protecting confidential data. Some data may not be appropriate to release because it may reveal trade secrets or other proprietary information. • Identify options for publishing as much data as possible without compromising data, for example, publishing aggregated data or publishing facility data.

This chapter presents a comprehensive framework for designing a national MRV system underpinned by the detail provided in preceding chapters. Ultimately, the design of the programme depends on the many predetermined country-specific factors, such as the governance system, policy objectives, capacity of government agencies and reports, and importantly, budgets. Ideally, the MRV system should be robust enough to provide reliable data to foster mitigation and realise emission reductions from the coal sector. Proper accounting of CMM, AMM and SMM identifies targets for immediate and effective action on emissions worldwide.

Policymakers should consider, holistically, the overall political landscape when developing an MRV programme. For example, the MRV programme is likely to be more successful if it is accepted by reporters, especially if they are independent commercial enterprises. As such, the implementing agencies might find it helpful to keep the industry engaged and establish formal and informal consultative processes with all stakeholders.

Another important consideration is whether other policies already in place incentivise or disincentivise accurate reporting. In countries where penalties above certain emission levels exist, reporters might find it preferential to underreport emissions. Thus, the design of the system, in such cases, should mitigate such disincentives. Procedures could be established to ensure that accurate reporting is beneficial and preferred by reporter, such as by establishing high default factors.

It is important to remember that an inventory, however detailed and complete, is not an effective instrument unless aligned with and used to monitor mitigation actions.

Appendices

Appendix 1. Measurements made with handheld equipment in coal mines

The most common approach to determining pure CH_4 flow in a mine airway is to combine use of a handheld anemometer to measure air flow velocity with air samples taken for CH_4 measurements using special vacuum bottles, "Gresham tubes" or sampling bags. Pitot tubes can also be used to measure air flow in combination with a differential pressure gauge. Thermometers and pressure gauges can be used to take temperature and pressure measurements. For example, the U.S. Mine Safety & Health Administration uses 10 millilitre (ml) vacuum bottles to take air samples during mine inspections. Handheld, calibrated methanometers may also be used to obtain CH_4 measurements; however, the lab analysis required for air samples may provide a higher degree of confidence in the measurements.

Air flow measurements are typically stated in terms of a volumetric rate, for example, cubic feet per minute (ft^3/m), cubic metres per hour (m^3/hr) or cubic metres per second (m^3/s). Air flow data may also be expressed in terms of actual measurements, standardised measurements or normalised measurements.

For mine ventilation air at working underground mines in the United States, these measurements are normally taken in the return airways at the base of an upcast exhaust shaft (also referred to as "Approaches"). Air flow and CH_4 concentration measurements are taken near the point where the return intersects with the upcast shaft. Persons responsible for taking measurements normally avoid entering the base of the upcast shaft due to the potential for fall debris which may cause injury. Because the ventilation system is operating under positive (very rare and not suitable for gassy mines) or negative pressure (standard practice in gassy mines), measurements from all returns leading to an upcast shaft provide a reasonably reliable estimate of CH_4 emissions from that shaft. In some cases, there are multiple returns leading to a single exhaust shaft. Where there are two or more returns to the exhaust shaft, the total airflow volumetric rate will be the sum of the airflow measurements from all returns leading to the shaft. The shafts CH_4 concentration will be the weighted average of the CH_4 concentration readings in each return.

Spot measurements should be taken on daily, weekly, monthly or quarterly basis, and it is not unusual for mine owner/operators to obtain monthly measurements through regular ventilation surveys.

Although taking measurements using this methodology is standard operating procedure at many mines in the United States for health and safety protocols, there are challenges associated with this methodology for GHG monitoring. Travelling to the upcast shaft from the surface can require a significant amount of time, potentially 2-4 hours per shaft. This may limit the ability of the owner/operator to pursue higher frequency sampling for GHG emissions compared to the frequency of ventilation surveys for health and safety monitoring. Another factor is the location of the methanometer (usually take readings over a grid of points) and the anemometer (a traversing method is used to average the airflow) when taking measurements. The incorrect location can adversely impact the accuracy of measurements. In many mines, measurement stations are marked to ensure consistency. Air speed and CH_4 concentration will vary within the cross section of a return airway. U.S. MSHA recommends that any measurements be taken at least 12 inches (305 mm) from the floor, roof and ribs, and measuring devices should be placed in a position to take a traverse or centerline reading of the cross section in the entry (US MSHA, 2013; US MSHA, 2019). [32] [33] Methane concentration measurements should also be taken during normal coal production times rather than shift changes or at other times when the mine has stopped production.

Grab samples and air flow measurements using some of the same or similar equipment (usually differential pressure across an orifice plate) can be used to measure CH_4 emissions from CH_4 drainage systems where drained gas is vented directly to the atmosphere. Bag or tube samples are sufficient to measure CH_4 concentration; however, handheld methanometers are unlikely to provide reliable measurements because any handheld measurements will be taken in open air, diluting the measurements. For air flow measurements, anemometers could be used to capture accurate flow measurements, but flow meters provide greater accuracy compared with a handheld anemometer. Where gas drainage systems use vacuum pumps to draw gas to the surface, flow meters or orifice plates will almost certainly be placed in the pipework as a standard operating procedure.

Where individual wells are vented at the surface with a lone vacuum pump, there may not be a flow meter on the vent necessitating the use of an anemometer or pitot tube to measure flow, applying a correction to account for the gas density. More regular sampling may be required at the individual surface wells than is used for the mine ventilation quantities as it is not unusual for a well to be operating one week and then shut within the next two weeks. Taking a sample in week 1 will skew the emission estimates if assumed to apply without adjustment to weeks 2 and 3.

The various manual CH_4 flow monitoring methods are summarised in **Table A1.1**.

[32] U.S. Mine Safety and Health Administration (U.S. MSHA) 2013. Coal Mine Safety and Health General Inspection Procedures Handbook. Handbook Number: PH13-V-1. February 2013

[33] U.S. Mine Safety and Health Administration (U.S. MSHA) 2019. Mine Safety and Health Enforcement General Inspection Procedures Handbook. Handbook Number: PH19-IV/V-1. December 2019

Table A1.1

Methodology and instrumentation for manual CH_4 monitoring at underground coal mines

Location	Measurement	Methodology	Equipment	Limitations
Upcast shaft	Airflow and CH_4 concentration exhausted from the mine upcast shaft (VAM emission)	Measure velocity and gas concentration (details as below)	Anemometer or pitot tube and methanometer or gas sampling devices (details as below)	Anemometer traverses can be difficult due to high air velocity and dust loading
Return airway underground	Airflow and CH_4 concentration in each underground return roadway leading to the upcast shaft	Average of four anemometer traverses within a known cross section, plus spot CH_4 sampling or sensing with a methanometer at six equally spaced points within the cross section	Suitable speed anemometer, current calibration chart, stopwatch, tape measure, notebook. Calibrated methanometer or sample tubes and Gresham pump, tedlar bags or other air sampling receptacles	Standard mine practice but only provides a spot reading and airflow can vary due to movement of materials and opening and closing of ventilation doors
CH_4 drainage station	Total drained CH_4 flow from the mine	Measure pressure differential across an orifice plate of known dimension	Differential pressure gauge, tubing. Calibrated, high-reading methanometer or gas sample tubes and pump	Reasonably accurate provided the orifice plate dimension is correctly known and there are no obstructions in the pipe
Surface gob well	Gas discharged from a passive vent or from a pump output vent	Fixed point velocity reading with application of a position factor and density correction	Pitot or small diameter anemometer and high reading methanometer	Low accuracy unless a calibrated continuous flow meter and gas monitor is installed
CMM utilisation plant	Cleaned, dry gas prior to use	Approved measuring instrument, calibrated by a third party and sealed at the customer interface	Flow, CH_4 concentration, pressure and temperature monitors	Manual monitoring not generally considered acceptable

Appendix 2. ACM0008, a UNFCCC approved consolidated methodology for abatement of CH_4 from coal mines.

ACM0008 was developed for use in CDM and JI Project Design and Development (PDD) at working surface and underground coal mines and also abandoned coal mines. The UNFCCC review process allows for continuous improvement of the methodology. Additions and improvements to the methodology can be submitted by stakeholders and revisions to the methodology are discussed and incorporated by the Executive Board (EB) of the UNFCC.

While the methodology is detailed and rigorous to ensure that certified emission reductions (CERs) thus generated are credible, the general principles are equally applicable to a national MRV programme:

- Need for compliance of standardised baseline scenarios with safety regulations
- Clear definition of applicability and exclusions
- Calculation of drained CMM, VAM, SMM, CBM and AMM emissions and mitigation
- Includes a relatively simple methodology for estimating AMM emissions but uncertainty is difficult to determine
- Requirement for archiving data for at least two years after the end of the crediting (reporting) period
- Use of calibrated measurement equipment.

Stakeholders have a role as consultees in project design, and CMM specific requirements are described in the methodology. A Designated Operational Entity (DOE), a qualified third-party, validates the project and submits a request for registration after obtaining host country approval. The outcome maybe a request for review or registration. The project participant is responsible for project monitoring in accordance with the approved methodology. Verification is carried out by a DOE to check that the claimed emission reductions were achieved according to the approved monitoring plan. Once satisfied, the DOE issues a written certification. The UNFCC Secretariat undertakes a completeness check and the verification report is vetted by the Secretariat and the EB. If there is no request for review the CERs are issued. A CDM registry records holdings of CERs.

The process is time consuming and costly and, therefore, only relevant for large projects. Nevertheless, while it was applicable in China, the CDM significantly expanded development of CMM utilisation and destruction projects. The price of CERs depended on the demand for offsets from the EU ETS which in turn was determined by the issuance of allowances to the capped entities. Failure to address an imbalanced market led to a crash in carbon price, seriously damaging the investment credibility of carbon markets.

In the context of MRV, ACM0008 provides a useful reference document for:

- Aiding the design of a CMM, AMM and SMM emissions monitoring programme
- Identifying mitigation options and
- Understanding potential emission accounting problems.

Appendix 3. Practical considerations for estimating AMM emissions

Many countries face challenges in quantifying national CH_4 emissions from abandoned mines. Estimating CH_4 emissions from an abandoned coal mine involves predicting the emissions of a mine from the time of abandonment to the inventory year of interest. While some monitoring of abandoned shafts exists, it is by no means universal. Methodologies for assessing emissions of AMM have been developed by various organizations in different countries, e.g., U.S. EPA, Defra in the UK and the Clean Energy Regulator in Australia. These methods are based on modelling assumptions or hybrids involving model forecasts together with measured data from shaft vents.

The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the flow capacity of the mine. Once mining ceases, no new emission sources are generated, and gas flow will decline. The limited data available on abandoned mine emissions indicate that emissions typically follow a hyperbolic type of decline curve. Decline curves, developed for specific basins or regions, can be used to forecast gas emissions from abandoned mines. For a particular mine, the curve is applied to the CH_4 emission rate of the subject mine at abandonment.

IPCC guidelines were modified in 2019 to include methodologies for estimating national AMM emissions along the lines of Tier 1 through 3 methodologies for estimating emissions from working mines. In addition to those guidelines, estimation of AMM emissions must also consider the method of underground mining when active as longwall mines are more likely to continue emitting CH_4 after abandonment due to the influence of the caving method on other gas-bearing strata. It is also important to understand that the availability and quality of data will be variable depending on the age of closure and whether any monitoring systems were installed for safety, environmental or utilisation reasons. Therefore, it may be beneficial to supplement existing data with field investigations. Also critical is to accurately assess the impact of groundwater recovery and intrusion to the extent possible. A cut-off date should be determined for each coalfield area beyond which emissions are considered negligible for estimation purposes. The longer time has elapsed since abandonment, the greater the chance of flooding. Calculation of emissions and emission reduction potential will almost certainly entail development of a type-curve to estimate gas production from mine closure. The following sections provide further detail on these considerations.

IPCC methodologies

The IPCC guidelines, as modified in 2019, include methodologies for estimating national AMM emissions. The principles are summarised below; full details can be found in the original document (IPCC, 2019).

A Tier 1 approach for developing an AMM emissions inventory, derived largely from methods developed by the US Environment Protection Agency (Franklin *et al*., 2004), is based on the total number of coal mines abandoned in a particular time interval, adjusted for the fraction considered gassy (i.e., exceeding 2,800 to 14,000 m^3/d, or 0.7

to 3.4 Kt, per year when working). Empirical emission factors were derived for each past year, the factors decrease with increasing time into the past.

While the methodology mentions that emissions from mines that are flooded can be ignored, it proposes that if there is no knowledge of flooding, the assumption should be made that all mines remain unflooded; an unlikely scenario in many instances which will lead to overestimation of emissions. High and low values of default values for the percentage of mines that are gassy are provided for each time interval of closure.

The Tier 2 approach is similar to the Tier 1 but makes use of coal basin or country specific information, when available, such as working mine emissions prior to closure. In the absence of any measured data, default values are provided to use as a last resort.

The Tier 3 methodology involves more detailed work and includes:

- Establishing a nationwide database of mine closures with relevant mining, geological and hydrological information together with dates when mine ventilation ceased
- Estimating emissions based on measured emissions prior to and after closure and/or an emissions model.
- In the absence of measured data, calculating emissions using an appropriate decline curve or modelling approach for openly vented mines, sealed mines or flooded mines. An emission factor or quantity is calculated using the selected decline equation or modelling approach for each mine and the number of years between abandonment and the inventory year. This might be considered a Tier 2/Tier 3 hybrid approach.
- As with the other methods above, the abandoned mine emissions are summed to provide an annual inventory.

The above methods are not definitive and other approaches, Tier 2/Tier 3, have been developed, the most significant being the incorporation of flooding rate through interpretation of coalfield and regional hydrology (Kershaw, 2005).

Reasonably accurate inventories are required to facilitate effective mitigation policy and action. Gathering relevant information requires close liaison with mine operators, mine plan, hydrological and geological repositories. and the participation of local mining expertise. There is no substitute for field investigation, and ultimately the observations could prevent wasted effort on erroneous forecasting and also help development of mitigation strategies.

Relevance of mining method

In comparison with longwall mining methods, room-and-pillar mines will, in general, emit significantly less gas in similar geology. National abandoned mine emission inventories will, therefore, largely relate to emissions from abandoned deep, longwall mines.

Availability and quality of data on abandoned mines

The availability and quality of data will vary depending on the age of closure and whether any monitoring systems were installed for safety, environmental, or utilisation reasons:

1. Mines already closed: limited gas and water data may be retained in archives, mine plans may be available and the number of abandoned mines will be recorded in most instances.
2. Recently closed mines: limited, medium quality data may be available.
3. Abandoned mines with monitored gas control vents: direct measurement data can be used to help define a decline curve but may lead to understated emissions if unidentified emission locations are present e.g., unsealed old mine entries.
4. High quality measured data from continuous monitoring should be available at abandoned mines where AMM extraction and utilisation or destruction by flaring is being practiced. The data can be used to produce a local/regional decline curve although emission quantities may be overstated as a result of the mechanical extraction process.
5. Future planned closures: working mines will hold a rich array of information much of which may be destroyed after closure. Such high-grade information should be gathered while access is available. At the same time there is an opportunity to engineer the closure process to facilitate gas and water monitoring and also AMM use/mitigation should a feasibility study indicate commercial viability.

Investigation and field work

Modelling with limited data can be used to estimate emissions but without an understanding of the mining, gas and hydrological setting, large errors can arise. Basic field investigation can help identify emission locations, provide spot pressure, gas flow and concentration measurement data, and where practicable, facilitate groundwater monitoring. A necessary action, should significant AMM emissions be encountered, is the design and monitoring of mitigation measures. Site inspection is also a necessary first step in such a process.

Impact of ground water recovery

Arguably, the most important AMM emission control factor is groundwater recovery. Groundwater and aquifers are disrupted by deep mining where longwall caving methods of working are used. Strata water is either pumped out of a mine or pumped into lower workings that have been abandoned. When a mine closes, pumping ceases and the water begins to rise in the workings, progressively isolating gas sources and reducing emissions. However, in some locations, pumping may be continued from a shaft or borehole to protect neighbouring mines from water inrush hazards, to protect an aquifer or to prevent surface discharge of acid mine water.

AMM emission estimation and forecasting should take into account:

- Areas where mine water has fully recovered, but some workings remain above the recovered water level. If workings are few and of low gas content this can be ignored. Calculate the gas resource above water and/or monitor vents. Check for emissions and investigate unusual occurrences.

- Areas where mine water has fully recovered and there are no mine workings above the water level can be assumed to have no significant emissions unless tests show otherwise, in which case, the origin of the gas warrants investigation.
- Areas where mine water is continuing to recover require accelerated attenuation of emission curve. The period over which emissions continue will depend on the rate and height of water recovery. Calculate gas resources above water versus time and/or monitor vents.
- Areas where mine water recovery is controlled by the pumping of mine water either to protect existing mines or to prevent contamination of an aquifer or a surface water course. In this instance, emissions could continue over a long period of time. Calculate gas resources above water and/or monitor vents.

Mine water recovery rate can be determined in two different ways:

1. By applying a permeability function that decreases the inflow of the workings into the mine depending on the volume of the workings that remain unflooded. Water level data from open shafts and boreholes studied in the UK indicate that water recovery after mine abandonment follows a predictable exponential curve similar to the recovery in any aquifer following pumping (Kershaw, 2005).
2. By using a geometric model based on void filling in each worked seam that is derived from mine plans and residual void assumptions. A simple approach is to assume a linear flooding rate based on measured water pumped during mining having subtracted volumes of service water introduced for the mining process e.g., for dust suppression.

Date of abandonment

A cut-off date should be determined for each coalfield area beyond which emissions are considered negligible for estimation purposes. The longer time has elapsed since abandonment, the greater the chance of flooding. Hence emissions on average are likely to be negligible after a certain date. The cut-off could be as short as 5 or 10 years after closure in mining area where rapid groundwater recovery occurs. For a particular region or coalfield area, some basic field research should help to establish what ages of closure are generally still emitting. In some areas, an exception may arise in which gas continues to be emitted, and these should be monitored on a mine specific basis.

Quantifying potentially available gas

A robust process for determining likely AMM quantities that might be emitted or exploited for utilisation 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.

Gas availability for emission or utilisation 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 (AMM BPG).

Derivation of decay curves

Estimation and forecasting of AMM emissions, relies on an empirical decline curve which is only as good as the data used for its generation. Extrapolation for forecasting is fraught with uncertainty and therefore data should be constantly gathered to enable the decline trend to be confirmed for a particular mine. In addition to gas flows at and immediately after closure, data to aid the construction of a decline curve can be obtained using:

1. Monitored data from abandoned mine vents
2. Measured data from deep mines under care and maintenance with no coal production
3. Measured data from working deep mines experiencing long stoppages due to such problems as geological, technical, safety or financial, or protracted industrial action
4. Measured CH_4 flows extracted and utilised (if the results are applied elsewhere where no extraction is taking place, emissions maybe overstated as more gas could be extracted under suction prior to flooding than would be emitted in the absence of mechanical extraction)
5. Measured CH_4 flows extracted and flared. At the relative low pumping rates, emissions may not be significantly overstated.

Simplifying data capturing for the national AMM emissions inventory

The coalfields or other distinct regional units should be examined for the mining situation, groundwater recovery and residual-gas-in-place estimates. In designing the methodology, the following should be considered:

- Wherever practical, emissions should be determined on an abandoned mine by mine basis.
- The most recent, and forthcoming, gassy mine closures will be the most significant emitters and it is highly recommended that detailed information on gas resource and emission rates is gathered from these locations.
- In areas with rapid flooding, it may be possible to disregard emissions from any mines more than, say, 10 years old. Thus, the importance of hydrological studies is illustrated.
- In areas with low gas content coal seams or where, historically, mining has been intense and few unworked seam gas sources remain, emissions may be low and not necessarily significant.
- In heavily mined areas where shallow workings may be present, gas could be arising from diffuse sources and may not be easily measurable. In such instances, surface flux estimates from atmospheric sampling or airborne or satellite may provide indicative values that can be used.

Appendix 4. Satellite systems (active sensors) capable of observing CH_4 emissions and concentrations

The following satellites and satellite systems are equipped with sensors capable of detecting CH_4 emissions. These systems can vary in coverage from global to targeted to a specific location. While some satellites are private, many of the satellites are publicly funded and monitor the atmosphere on a regular basis using active sensors. The international Committee on Earth Observation Satellites (CEOS) is pursuing a 'virtual constellation' that allows coordination of these satellites to deliver atmospheric monitoring, including CO_2 and CH_4 (CEOS, 2018).

"Nominal detection threshold" describes the minimal leak rate the system is expected to detect and quantify. "Pixel size" describes the size of the smallest block on the Earth's surface that a satellite detects. When pixels are combined, they create an image. The larger is the pixel size, the lower is the resolution, whereas small pixel size results in higher resolution.

Coverage	Instrument (Agency)	Launch	Nominal detection threshold, (kg/hour)	Pixel size (km x km)
Global	SCIAMACHY (ESA)-retired	2003	68,000	30 x 60
	GOSAT (JAXA)	2009	7,100	10 x 10
	TROPOMI (ESA, NSO)	2017	4,200	5.5 x 7
	GOSAT-2 (JAXA)also known as "IBUKI-2"	2018		10 x 10
	Sentinel-5 (ESA)	2022	4,000	7 x 7
	CO2M (ESA)	2026	1,000	2 x 2
	GeoCarb (only observes the Americas) (NASA)	2024	4,000	10 x10
Regional	MethaneSat (Environmental Defense Fund / ESA)	2022	500-1,000	0.1 x 0.4
Targeted	GHGSat-D ("Claire")	2016	1,000	0.05 x 0.05
	GHGSat-C1 ("Iris")	2020	110	0.025 x 0.025
	GHGSat-C2 ("Hugo")	2021	110	0.025 x 0.025
	GHGSat (3 additional satellites)	2022	110	0.025 x 0.025
	MethaneSat (Environmental Defense Fund / ESA)	2022	500-1,000	0.1 x 0.4
	TANGO (Copernicus)	2024	500-1,000	0.3 x 0.3
	Methane Remote Sensing Lidar Mission (MERLIN)	2024		

Source: adopted from Elkind et al., 2020, JAXA, nd, Crisp et al., 2018, GHGSat, 2021.

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Best Practice Guidance for Effective Management of Coal Mine Methane at National Level:

Monitoring, Reporting, Verification and Mitigation

While Methane (CH4) is the second most prevalent anthropogenic greenhouse gas (GHG) after carbon dioxide (CO2), the Global Warming Potential (GWP) of the former is 28-34 times higher than that of the latter. Coal mining is a major source of methane emissions, accounting for about 12% of global total anthropogenic emissions of that gas. Most emissions come from underground working mines, but those from abandoned mines are raising.

Action on methane requires solid understanding of emission sources at national, subnational, and local levels. Only with reliable emissions data, can policymakers design effective GHG policies, evaluate mitigation opportunities, and comply with their international climate commitments.

National monitoring, reporting and verification (MRV) programmes can not only help countries better understand the contribution of coal mining to their overall methane and GHG emissions, but also identify opportunities for mitigation. In particular, MRV can help assess and track the effectiveness of the adopted climate policies. Setting up efficient MRV schemes is also important to deliver on international climate commitments in the context of the Paris Agreement.

Information Service
United Nations Economic Commission for Europe

Palais des Nations
CH - 1211 Geneva 10, Switzerland
Telephone: +41(0)22 917 12 34
E-mail: unece_info@un.org
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