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Best Practice Guidance on Ventilation Air Methane (VAM) Mitigation

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UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

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Acronyms

ACCU	Australian Carbon Credit Unit
AR	Assessment Report issued by IPCC. The sixth assessment report, AR6, was fully published in 2023. The GWP estimates (of AR6) were updated in 2021
ALARP	As Low As Reasonably Practicable
CAPEX	Capital Expenditures, i.e., investment costs
CARB	California Air Resources Board
CCS	Carbon Capture and Storage, including capturing emissions of CO_2, transporting them to, and pumping them into their permanent storage site, e.g. in a depleted oil and gas field.
CDM	Clean Development Mechanism under the rules of the Kyoto Protocol
CERs	Certified Emission Reductions
CH_4	The chemical formula of methane
CO_2	The chemical formula of carbon dioxide
CO_2e	Carbon dioxide equivalent
CTO	Catalytic Thermal Oxidizer
ETS	EU Emission Trading Scheme
Évasé	The duct of a mine ventilation system located above the ground
GHG	Greenhouse Gas
GMI	Global Methane Initiative
Gob/Gof	Area of collapsed strata after mining
GWP	Global Warming Potential
GWP_{100} / GWP_{20}	GWP compared to CO_2 on a 100-year basis / on a 20-year basis
HAZOP	Hazard and Operability Study
IMEO	International Methane Emissions Observatory
IPCC	Intergovernmental Panel on Climate Change
LEL	Lower Explosive Limit
LFL	Lower Flammability Limits
m^3/h	Cubic metre per hour
MAIT	Minimum Auto Ignition Temperature

MW	Megawatt
MWe	Megawatts electric, refers to the electricity output of a power generation plant
OPEX	Operational Expenditure, meaning operating expenses
PFCs	Perfluorocarbons (group of chemical compounds)
RCO	Regenerative Catalytic Oxidation/Oxidizer
RTO	Regenerative Thermal Oxidation/Oxidizer
Scfm	(Standard) Cubic Feet per Minute
TER	Thermal Energy Recovery
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollars (US $)
US EPA	United States Environmental Protection Agency
tCO_2e	Metric tonnes of CO_2 equivalent
UNECE	United Nations Economic Commission for Europe
VAM	Ventilation Air Methane

EXECUTIVE SUMMARY

In a world increasingly committed to reducing greenhouse gas emissions, and in which fossil fuels continue to dominate the global energy mix, mitigation of Ventilation Air Methane (VAM) emissions from coal mines stands out as a very effective opportunity to slow down climate change.

It is likely that many existing and planned coal mines will continue operations for at least the next two decades. However, as long as underground coal mines keep operating, many of them will emit large amounts of methane into the atmosphere. A single large ventilation shaft at an operating mine can release approximately 50,000 tonnes of methane annually. This single source emission has a global warming impact equivalent to that of 2 million cars with combustion engines. Therefore, mitigation of VAM emissions should be a priority, as it offers an immediate and effective way to reduce atmospheric methane levels and slow the progression of climate change.

Efficient VAM mitigation technologies have been proven in several commercial-sized, long-term projects. For such projects to be economically viable, the value of emission reductions needs to be at the level of around USD 20 per tonne of CO_2e. Therefore, compared to many other climate change mitigation actions, VAM mitigation is cost-effective.

However, there are several challenges to effectively reducing VAM emissions, including:

1. The methane concentration in ventilation air is extremely low, typically ranging between 0.1% and 1%; and
2. The volume of air ventilated through a mine shaft is very large, with some shafts venting over 1 million cubic metres per hour.

To date, only one technology, namely Regenerative Thermal Oxidation, or RTO, has demonstrated to operate reliably at coal mines. RTO technology, developed in the 1970s to clean industrial emissions (different kinds of volatile organic compounds - VOCs) from the air, has been proven to effectively operate at methane concentrations as low as 0.2%. Other potential VAM mitigation technologies, primarily different catalytic processes, are currently under development and pilot testing.

The Paris Agreement (2016) requires its almost 200 signatories to take the necessary steps to limit global warming to below 2 degrees C. The Global Methane Pledge (2021), which has been endorsed by 159 countries, aims to collectively reduce methane emissions by 30% by 2030. Additionally, various smaller- scale initiatives have been launched, with countries committing to emission reduction targets.

This Best Practice Guidance is designed to provide:

- Policy makers, governments, and climate-related funds with the justification for securing financial support (at the level of USD $20 per tCO_2e for at least first 4-5 years of plant operation) needed to make VAM mitigation projects economically viable.
- Mine operators and owners, as well as investors with (1) an understanding of the key aspects of VAM emissions mitigation; (2) a list of potential uses of VAM's inherent energy; and (3) a basis for assessing the feasibility of VAM mitigation plants.
- Mining engineers and VAM equipment suppliers with a foundational understanding of technology and its integration into the coal mine environment.
- Everyone interested in that matter with a practical 8-Step model for preparing for potential VAM projects.

The report offers an understanding of the nature and the challenges of mitigating coal mine VAM emissions, provides an overview of strategies to overcome these challenges, and discusses the economics of proposed solutions. For ease of reading, the body of the report is succinct, presenting accessible and understandable information, while more detailed data and inputs are provided in the Annexes.

1. Methane, Coal Mine Methane and VAM

1.1 Basic information on methane

Methane is the smallest hydrocarbon gas molecule, consisting of one carbon atom and four atoms of hydrogen - CH_4. The natural rate of oxidation of methane is slow, but it increases rapidly with the temperature, especially around 850-900°C, as illustrated by **Figure 1**.

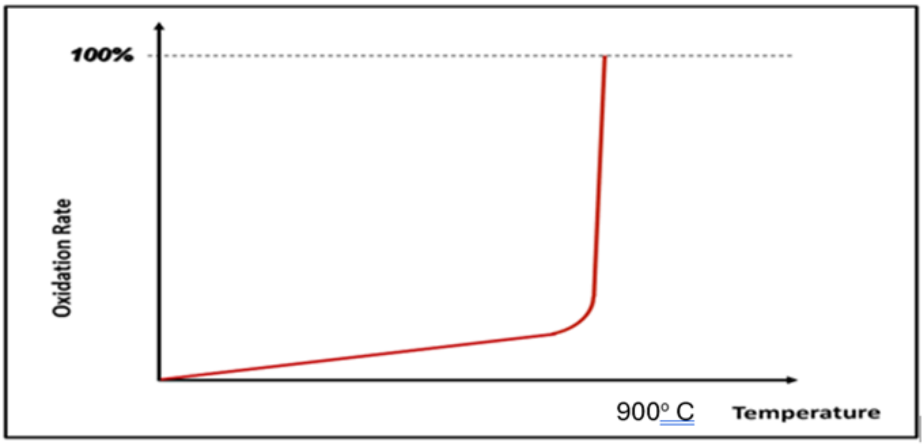

Figure 1*: Oxidation rate of methane*

1.2 Methane and Climate Change

Methane is an important greenhouse gas, second only to CO_2. As compared to the latter, the volumes of its emissions are smaller, but its capacity to retain heat in the atmosphere is much greater. As a result, it offers great mitigation potential. For more information see **Chapter 6** and **Annex 1**.

1.3 Coal mine methane and VAM

Coal associated methane is a byproduct of the coal forming process. It is trapped in coal and the surrounding strata and may be released during coal extraction activities. The amount of methane in coal varies, depending mainly on the depth of the deposit, rank and type of coal, and its permeability.

Methane released during coal extraction activities is termed coal mine methane (CMM) and its released volumes depend on coal permeability, mine design and operational factors, as well as on the size of coal production. What also needs to be taken into consideration is whether there were any pre-mining methane drainage activities previously conducted on a given site.

Since methane is highly explosive in concentrations ranging between 5% and 15% in the air, it represents a major coal mining safety issue. A spark that occurs in a mine with a methane concentration in its explosive range will ignite the gas causing an explosion. This is often followed by a second explosion of the coal dust that becomes airborne during the initial methane ignition. Such accidents typically result in widespread destruction and many casualties.

In order to avoid such incidents, large volumes of air (ventilation air) are passed through a mine to dilute methane to well below its lower explosion limit (i.e. well below 5%). Typical VAM concentrations in coal mines are around, or below 1%, but the exact limits vary among different jurisdictions.

The downside of the described ventilation process is that it results in huge volumes of methane-bearing ventilation air being continuously exhausted from the mine to the atmosphere for the whole time of mine operation[1].

In many cases, when the ventilation system alone is insufficient to keep methane concentrations in a mine on a safe operating level well below the explosive threshold, methane drainage is carried out as a supporting solution.

The primary pathways for fugitive methane emissions from an operating mine include:

- Ventilation Air: methane present in the ventilation air, known as Ventilation Air Methane (VAM)
- Pre-Mining Gas Drainage: the process of drilling into either the coal seam to be mined, or into the seams directly above or below it, to extract gas prior to the commencement of mining activities
- Post-Mining Drainage: the release of gases concurrent to, or after mining activities
- Abandoned Mine Methane: the release of gas from any mine portal, adit, or shaft after the mine has ceased its operation

Methane drainage may be carried out by drilling into the seam that is being extracted and/or overlying coal seams, other strata, and the collapsed and mined-out portions of the mine (gob or goaf). It is done to minimize the amount of post-mining methane releases into the workings and the ventilation air. The amount of methane in drainage gas depends on many aspects, such as the depth of the mined coal seam, sorption parameters and permeability of that coal seam and the surrounding strata.

Methane drained from the coal bearing strata prior to the coal extraction (pre-mining drainage), which is also an option, reduces the amount of ventilation air required to dilute the gas released during mining. This improves safety and reduces energy required to operate the mine ventilation fans.

Pre-mining drainage gas usually contains more than 90% methane and can be used to produce electricity, generate heat, or balance/augment methane concentration in ventilation air to support the process of energy generation from VAM treatment.

Postmining drainage gas is released from the collapsed strata occurring in the wake of mining a coal seam. The methane concentration from this area is called gob- or goaf-gas and typically has a lower concentration than pre-mining drainage gas. In most cases, however, it is still sufficiently high (often 60% and higher), to be utilized as a fuel for either gas engines generating electricity, or for heating. In most cases, it is extracted from the workings through a closed pipeline network that keeps it separate from any potential ignition sources. In addition, technologies to control flame propagation risk, such as e.g., flame arrestors in pipework, are readily available, further increasing safety of mine drainage

[1] One large coal mine ventilation shaft can have the same impact on global warming as emissions from 2 million cars (See **Chapter 6**).

systems, particularly during extraction plant start up and shutdown, when flammable gas mixtures may pass through the system.

Globally, around 70% of all coal mine methane is released in the atmosphere as VAM. Despite its very low methane saturation, the enormous volume of air coming out of ventilation shafts accounts for the majority of total CMM emissions. Consequently, any effective CMM mitigation efforts must include VAM abatement.

1.4 The difficulty in processing VAM

As discussed above, gas drained prior to and during mining, as well as gas extracted from the already mined areas (where gas continues to flow from the collapsed mining galleries and the surrounding strata) tend to have sufficiently high methane concentration to fuel special gas engines and/or to operate flares. While it is technically possible to operate both at concentrations of down to 20% and even lower (down to approximately 8%), most national mine safety regulations prohibit the use of low concentration methane in order to ensure that the explosive range of methane in air (5% to 15%) is not reached. This reduces the likelihood of flammable gas traveling in the gas extraction pipework.

The difficulty of processing VAM results from a combination of two factors: the extremely large volumes of ventilation air and the extremely low concentration of methane contained in the air stream (typically between 0.1% and 1%). To effectively tackle the full problem of emissions, the entire volume of the ventilation air needs to be processed. This represents a significant challenge. While emissions into the air from the industrial sector are typically in the range of tens of thousands of cubic metres per hour, over the same period of time a large mine shaft can emit as much as a million cubic metres or more.

Figure 2 illustrates references for various coal mine methane concentrations, relating to the fact that only 0.2% is required to keep the RTO VAM oxidizing process going, and 0.5%-1% allows for energy recovery and use.

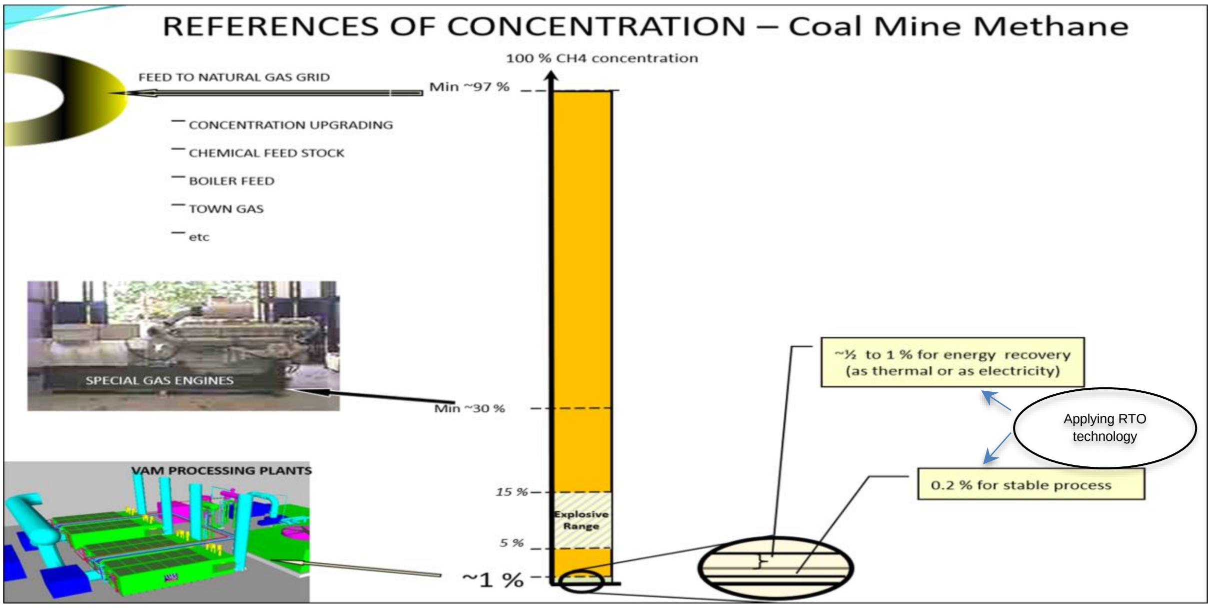

***Figure 2**: VAM concentrations in relation to other levels of coal mine methane concentrations*

2. VAM Technologies Overview

2.1 Technologies for processing VAM

Various technologies have been tested to process and utilize ventilation air methane. Most of them, however, have difficulties addressing one or both of the main VAM challenges, i.e. very low concentrations of methane and very large air flows. (See a summary of technologies that have been tested for VAM processing in **Figure 3**.)

2.1.1 Combustion Air to Power Plants/Engines

On the rare occasion of having a major power plant located near a coal mine's ventilation shaft (there are a few such so-called "mine-mouth power plants" e.g. in China), the ventilation air could be used as combustion air, providing VAM as a supplementary fuel to the energy generation process at the power plant. Such a solution, however, is applicable only if the plant is indeed placed adjacent to the évasé (a big exhaust duct with widened outlet opening, designed to reduce fan energy losses of the mine ventilation shaft) thus removing the necessity of moving the enormous volumes of ventilation air through an extended ductwork, which taking into consideration its required dimensions would be very expensive to install. If the above-indicated conditions are met, the described solution is likely to be the most cost-effective way to utilize VAM as an energy source. Consequently, the demonstration of such opportunities should be encouraged. Since such a project would be one of the first of its kind, special attention would need to be given to safety concerns.

Using coal mine ventilation air as combustion air for engines is also a possibility. This option needs to consider the very large volume flows involved, as well as the fact that dust particles in the ventilation air might be abrasive or disturb the function of the engines in some other ways.

2.1.2 Lean Gas Turbines

Lean gas turbines have proven to be successful in operating on very lean gas feeds containing as little as 2 to 3% methane. However, that range of concentration is too high to be applicable to VAM emissions (typically between 0.1 and 1.0%). One technology has reported successfully operating a (small) turbine at 0.8% methane concentration by applying a catalyst (see further **section 2.1.4**). The scale of air volumes that the turbines would need to process to mitigate VAM emissions constitutes, however, an additional obstacle for applicability of this technology.

2.1.3 Concentrators

Industrial concentrators operate in a fashion that captures the target molecule(s) from a larger air flow and then releases them into a smaller air flow. Over a longer period of time, the bed material of the concentrator catches (adsorbs) the molecules of the substance to be concentrated. Then over a shorter period the bed material releases (desorbs) the caught molecules into a heated, smaller air flow, thereby obtaining a higher concentration of the targeted gas.

Methane is a small molecule, which, unfortunately, is difficult to both adsorb and to desorb. While there have been some interesting developments in that field, by 2024 no commercial scale solution has been presented to the market. From a VAM perspective, methane concentrator technologies are of interest primarily as a means of increasing concentrations that are too low for commercial processing (i.e. below the 0.2%, which is the limit allowing RTO oxidizers maintain a self-sustaining oxidation process).

2.1.4 Catalytic processes in general

Catalysts can be used to initiate oxidation at conditions in which it would otherwise occur at a low or very low rate.

The general reason for pursuing the use of catalysts in industry is to lower the temperature required for oxidation, for example when exhaust flue gases are at a bit lower temperature than normally needed to oxidize given emissions. In such cases, by applying the right catalyst, oxidation can take place without the necessity of adding energy. Furthermore, there can also be an interest in using catalysts to obtain given chemical reactions, e.g. in the chemical industry.

While methane oxidation is a difficult process to catalyze, some promising developments have already been made. Several potential suppliers of the technology announced that they expected to proceed from pilot scale testing to field testing in 2024 or 2025.

A common issue with processes using catalysts is that the catalysts can be susceptible to being "poisoned". Poisoning occurs when unwanted chemical elements and molecules bind to the catalyst, halting the process. For instance, many catalysts are sensitive to sulphur. In the case of VAM processing the presence of calcium dust or silica dust could also be an issue. In addition, under normal use, a catalyst needs to be periodically replaced, which adds to the plant's operating costs.

A special catalytic process is RCO, which is presented in **section 2.1.7** below.

2.1.5 Industrial thermal oxidizers in general

There are three main types of industrial thermal oxidizers: RTO (Regenerative), RCO (Regenerative Catalytic), and Recuperative Oxidizers. The last one includes continuous fuel feed to an open flame and therefore it is too expensive to be a viable option for (the very large air volumes processed in) VAM mitigation.

2.1.6 Regenerative Thermal Oxidizers, RTO

In 2024, the only technically and commercially proven type of technology to successfully process VAM emissions are Regenerative Thermal Oxidation (RTO) installations. They have proven capable of sustaining operations on methane concentrations as low as 0.2%, effectively handling typical operational swings in concentrations. In addition, when methane concentration is around +0.5% or more, RTO installations allow for utilization of the energy released in the VAM oxidation process as an extremely lean fuel for energy production (for more information on RTO technology see **Annex 2**).

2.1.7 Regenerative Catalytic Oxidizers, RCO

As discussed before, the main purpose of employing catalysts is to lower the required oxidation temperature of methane and thus save energy and money. However, while there have been attempts to use Regenerative Catalyst Oxidation (RCO) for VAM processing, as of the end of 2024 none of them have led to a commercial application of the technology.

2.1.8 Recuperative Oxidizers

This technology is not relevant for VAM mitigation due to excessive fuel consumption.

TECHNOLOGY	SPECIFICS	ISSUES	STATUS
Using ventilation air as **COMBUSTION AIR** with VAM as supplementary fuel	Primarily for power plants. This might to some extent be possible also for turbines and boilers.	Very large air volumes (especially for turbines or boilers). For turbines, dust in the ventilation air can be an issue.	"Mine mouth power plants" can be found e.g. in China.
LEAN GAS TURBINES	Have managed to operate on methane concentrations as low as 2-3%.	Typically, VAM needs to be combined with drained coal mine methane. Very large air volumes.	By end of 2024, only laboratory/pilot scale installations have been reported.
CONCENTRATORS	Increase CH_4 concentration.	Technical difficulties with methane. Need to process very large air volumes.	By end of 2024, no successful installations or trials officially reported.
CATALYST PROCESSES (See also RCO below)	Use of a catalyst to initiate a process for reducing methane emission.	A catalyst can be "poisoned", by e.g. Sulphur, and thus lose its function. Needs to be periodically replaced.	Globally, there are several catalyst solutions in pilot trials and laboratory scale demonstrations. In 2025, a number of field demonstrations are announced to be expected.
RTO, Regenerative Thermal Oxidizers	Need only 0.2% methane for self-sustaining oxidation process.	No significant issues for RTO suppliers with extensive experience in demanding industrial applications.	Proven technology for VAM. There are several installations with decade long good experience of operation.
RCO, Regenerative Catalytic Oxidizers	A Catalyst can lower the temperature needed for oxidation.	A catalyst can be "poisoned" by e.g. Sulphur and needs to be periodically replaced.	Several RCO solutions have been tried. By end of 2024, no success officially reported.
Recuperative Oxidizers	Since oxidation is maintained by an externally fueled flare, this technology is not relevant for VAM mitigation.	Need to add large amounts of fuel to keep the process flare going.	Not relevant for VAM mitigation.

***Figure 3**: Main technologies for addressing VAM emissions*

2.1.9 Conclusions on VAM mitigation technologies (sections 2.1.1 through 2.1.8)

- The most interesting option for VAM mitigation is to use ventilation air as combustion air, which, unfortunately, is available only on rare occasions when a large power plant is located in a close proximity to the ventilation shaft.
- As of the end of 2024, the only VAM mitigation technology proven on a commercial scale is RTO.
- There are half a dozen catalytic VAM mitigation technologies under development in the US, Europe, and Australia. It is likely that, once evaluated, some of them might emerge as alternatives to RTO.

2.2 VAM processing barriers and potential ways to overcome them

2.2.1 Methane concentration and air volume

The most challenging technical barriers related to VAM processing are an extremely low concentration of methane in ventilation air, and the enormous air flows involved.

VAM concentration

There are a number of industries other than mining, such as the chemical and petrochemical industries, that need to oxidize emissions as a part of their production processes. These processes are also characterized by very low concentrations of hydrocarbon gases. Since the early 1970s they have been successfully applying RTO technology, which has proven effective in addressing that challenge.

Cases of decreasing VAM concentration

Some coal mines experience decreasing VAM concentrations. This might be a result of e.g., increasing methane drainage operations prior to mining, mining into coal seams with a lower gas content, or decreasing coal production rates (due to e.g., decreased demand and the resulting lower contractual obligations, or using one working shift for maintenance rather than for mining).

These are the following measures that might be taken to keep VAM concentration at or above the minimum level required for mitigation (i.e. 0.2%):

- Review of underground ventilation air flows to reduce the volume of air moved by the main ventilation fans while still maintaining full safety in all parts of the mine (which requires taking such action as e.g., shutting off certain parts of the mine, or increasing the efficiency of the air flow in other ways). If this can be done, not only will it lead to less dilution of methane concentrations by ventilation leakage, but also to energy savings obtained from more efficient use of the main ventilation fans. However, mine companies are typically reluctant to apply that method due to safety concerns.
- Adding drainage gas at safe methane concentrations (greater than 25%) to the ventilation air flow infrastructure on the surface prior to entry into the VAM processing unit (see the installation by Eisenmann Environmental **in Annex 3**).

It is imperative that any measures aiming to raise VAM concentration are always taken with proper safety considerations, and after approval of the mine ventilation plans by the mine safety authorities of the respective jurisdictions. The safety of the mine must be the primary design criterion of any decision made.

Air volumes

As already mentioned, on multiple occasions processing VAM requires treating enormous quantities of methane-bearing ventilation air. RTO technology addresses this challenge by its modularity. A typical VAM RTO installation includes multiple modular RTO units, allowing for scaling up or down its VAM processing capacity as required by the actual ventilation air volumes at a given mine. With relevant design precautions taken, modularity permits also relocation of the equipment, which means that units no longer needed on one site can be moved to another one.

2.2.2 Energy content

Since the concentration of VAM is extremely low, it is difficult to directly utilize the energy released during oxidation. As already discussed above, to maintain the oxidation process RTO technology requires only 0.2% of methane content in the ventilation air coming to the RTO units. When the VAM concentration rises above that level, it becomes sufficient for energy recovery (see below).

2.2.3 Financing

Since the energy content of VAM is low, so is the income that VAM mitigation generates. As a result, VAM mitigation typically represents a cost rather than a profit to the operator. Therefore, to attract financing there must be a value attributed to methane emissions mitigation. It might come from either evading a cost (a penalty) that would otherwise be attributed for each emitted tonne of CO_2e, or from a revenue obtained for each avoided tonne. Governments need to decide which path is more suitable to the particular conditions and needs in their jurisdiction.

2.2.4 Safety

Due to the danger that methane poses to the personnel working underground, ensuring safe operation of any methane handling equipment in a mine is a top priority. Mine operators have extensive experience in handling methane in the underground environment. The main equipment element for this is the mine ventilation system. Any VAM mitigation infrastructure must be installed and operated so that it does not impact the operation of the ventilation system and conduct the ventilation exhaust to the VAM processing facility in a non-obstructing manner that guarantees the safety and integrity of the system as a whole.

Note that in each jurisdiction the legally defined maximum methane concentration in VAM is applicable to all parts of the underground mining galleries, which means that in the air mixture coming up through the exhaust ventilation shaft it might be lower. Therefore, in order to increase efficiency of the process, VAM concentration can be adjusted (closer to 25% of lower explosive limit - LEL) by adding methane drained from coal seams or the gob, prior to the VAM mitigation units. Such a procedure, however, often raises security concerns among the mine personnel and therefore must be designed and executed with the maximum possible degree of caution.

RTO technology suppliers with extensive experience from other industries are aware of the heightened safety concerns in the mines. They have decades of experience avoiding disruptions of customer's industrial processes and are familiar with precautions that need to be taken to avoid unexpected occurrences of sparks, flame fronts, and detonation fronts, as well as with the codes of conduct to handle those incidents if they, nevertheless, occur. They also know how to handle impurities present in the air flow in the form of dust and other harmful substances.

The above notwithstanding, at the beginning of each RTO system project, an extensive review of potential safety issues and the standard procedures for addressing them must be conducted by the RTO technology supplier and engage with the customer and authorities. The mine operator and government authorities charged with mine safety must be assured that commercially available equipment is designed to meet mine safety regulations and allow the installed systems to operate using acceptable safe practices, agreeing on what is considered As Low As Reasonably Practicable (ALARP).

2.3 Commercial VAM installations – case studies

Trial installations in the UK in 1994 and in Australia in 2001–2002 were the first, limited in time (up to a year of operation) demonstrations of the VAM processing capability of the RTO technology. In 2007 the first commercial scale installation was commissioned. Since then, several successful commercial scale projects, located primarily in Australia, in the US, and in China have been developed, confirming the effectiveness of the RTO technology (see **Annex 2**).

By 2024, around 20 VAM mitigation projects have been commissioned globally.

3. VAM RTO Technologies

3.1 Basic function of RTOs

3.1.1 Types of RTOs

RTOs function at the natural oxidation temperature of methane, i.e. 850-900ºC. The hot zone is completely enclosed, and the system is well insulated. As a result, it operates with very low heat losses.

There are three types of RTOs, depending on the number of heat exchanger beds that the polluted air (i.e. ventilation air in the case of coal mines) passes through (see **Annex 2**). In terms of technology and finance, the types suitable for VAM processing are single bed and twin bed RTOs.

For simplicity, to illustrate configurations and alternative ways of energy recovery, the Figures in **Chapter 3** of this report present only single-bed RTOs. Twin bed RTOs work in principle in the same way, with the main exception that in this case, hot air can be extracted directly from the combustion (oxidation) chamber (for differences and similarities in function of the two, see **Annex 2**).

3.1.2 Catalytic Thermal Oxidizer

The basic idea with a Catalytic Thermal Oxidizer (CTO) is that using a catalyst to lower the temperature required for oxidizing methane may allow to lower the pressure over the hot zone and thus save energy and money (raising the temperature increases the air volume, resulting in increasing pressure through the ceramic RTO-beds).

Catalysts must be replaced when its performance is degraded by contamination or "poisoning"[2]. Their replacement or onsite regeneration adds to the operating costs of the system. Nevertheless, in the future the use of a methane catalyst could potentially become of interest, provided that their durability and resistance to contaminants, especially sulphur, is improved. With a VAM oxidation catalyst successfully applied, a VAM RCO could handle a larger air flow (when heated, air takes more space), which means that the fan pushing the ventilation air through the RCO will require less energy per m^3 of air. This would have a positive effect on both CAPEX and OPEX.

Once proven in large scale demonstrations, evaluations will show if and how CTOs can provide any advantage over RTOs in the application for VAM mitigation.

In industry, CTOs are rarely used due to insufficient advantages over RTOs, combined with additional risks and costs involved. Suppliers of CTOs are normally the same companies as suppliers of RTOs.

3.2 Energy recovery from VAM RTO oxidation

VAM concentration in a coal mine ventilation shaft varies over time. See example in **Figure 4**.

[2] Poisoning occurs when a catalyst is exposed to chemical compounds that bind to the catalyst effectively reducing the active surface area of the catalyst, lowering its ability to function.

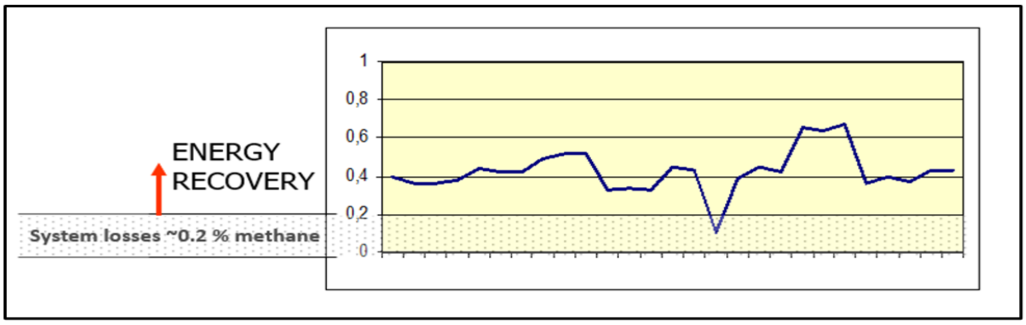

***Figure 4**: Example of VAM concentration variation over time*

When the content of methane in ventilation air exceeds 0.2% (which is necessary to maintain heat within the bed and thus sustain the oxidizing process), it becomes technically possible to recover heat contained in the surplus concentration and to use it:

(1) to generate steam for power generation (typically requires around 0.5% to 1%),
(2) for heating,
(3) for cooling (see **section 3.2.4**), or
(4) to provide heat for chemical processes.

Since the energy content of the first 0.2% is always "lost" to maintain the oxidizing process, the greater the concentration above 0.2% the better the yield of energy recovery. For instance, at 0.4% VAM, the energy of 0.2%, can be retrieved (0.4% minus 0.2%), while at 0.8%, that numbers grow to 0.6% (0.8% minus 0.2%) (see **Figure 5**).

Satisfactory conditions for energy recovery and utilization typically exist at VAM concentrations of around 0.5% and higher.

If a steady output of energy is of importance (e.g., to run a steam turbine at optimum), the energy content of ventilation air being processed can be stabilized by injection of drained gas prior to the RTO units. This allows for the methane content to be stabilized at suitable level, thus permitting to utilize the generated energy. However, due to already discussed security concerns, supplying VAM with any additional side streams of mine methane must be done with the maximum possible degree of caution in order to exclude the possibility of increasing risk of provoking any methane-related accidents.

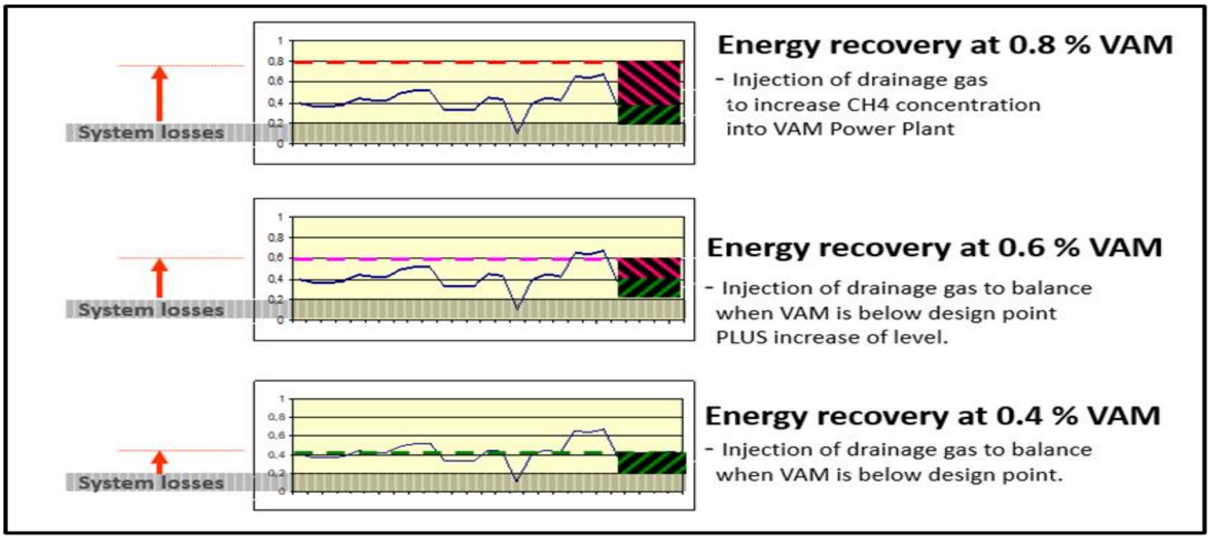

***Figure 5**: Energy recovery at different VAM (plus drainage gas) concentrations*

The highest efficiency in terms of energy and project economics is obtained when the end-user of the generated thermal energy (any building to be provided with heating, or an industrial process requiring heat) is located reasonably close to the mine ventilation shaft.

3.2.1 Thermal energy

The most efficient way to recover thermal energy from an RTO is to utilize tubes embedded inside it to generate hot water, hot oil, or steam (see **Figure 6**).

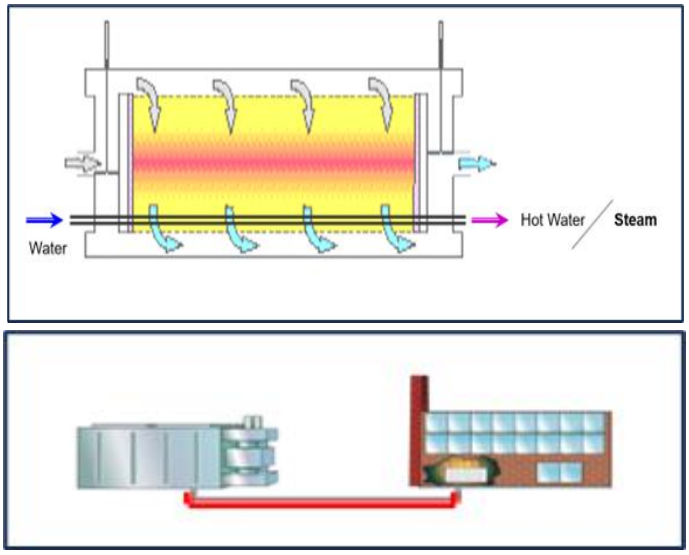

***Figure 6**: Embedded tubes generating hot water/oil/steam for large nearby thermal use*

When the potential utilization of thermal energy is relatively small, a secondary heat exchanger placed on the exhaust from an RTO can be sufficient (see **Figure 7**).

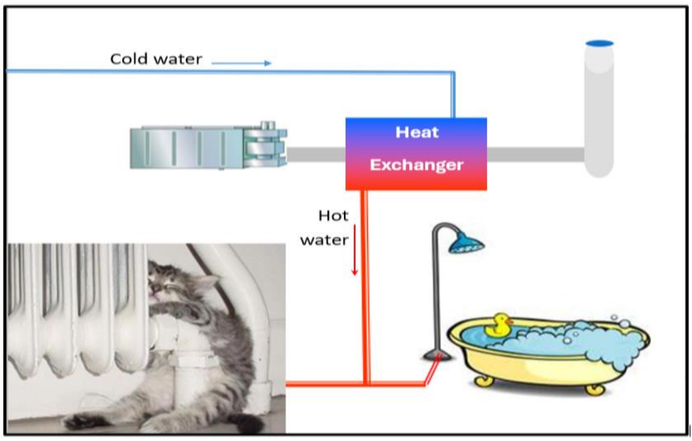

***Figure 7**: Heat exchanger on the exhaust providing heat for small-scale thermal use*

3.2.2 Thermal energy for generation of electricity

To generate high grade steam through embedded tubes, water is first passed through boiler tubes in the RTO's bed. When heated, some of the water is converted to steam as illustrated in **Figure 8**. The mixture of steam and water is then led to a steam drum, from which pure steam is fed back into the RTO's bed, this time through superheater tubes configured in such way that the superheated steam leaving the system has the characteristics matching the requirements of a steam turbine of the steam cycle (see **Figure 9** showing an example of the principle steam cycle of the VAM Power Plant WestVAMP, commissioned at the WestCliff Colliery of BHP Billiton in Australia in 2007).

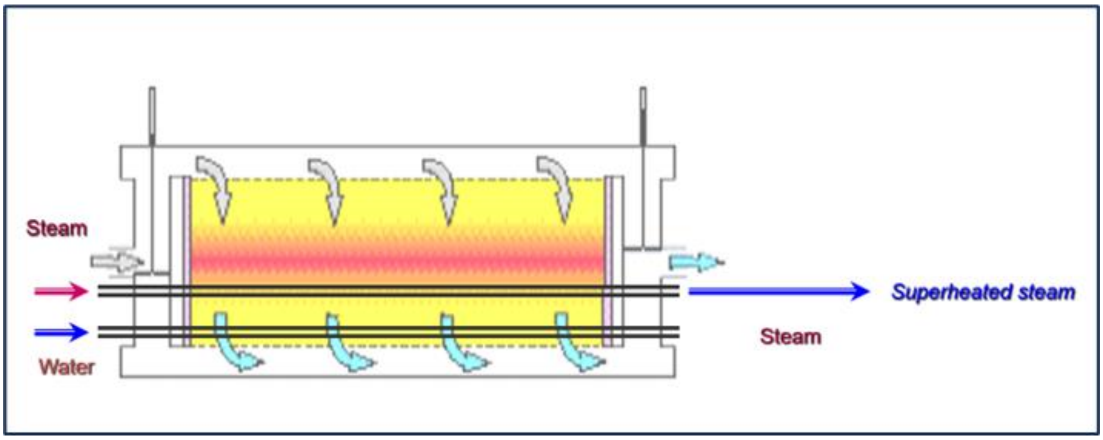

***Figure 8**: Boiler tubes and superheater tubes embedded in a Single bed RTO*

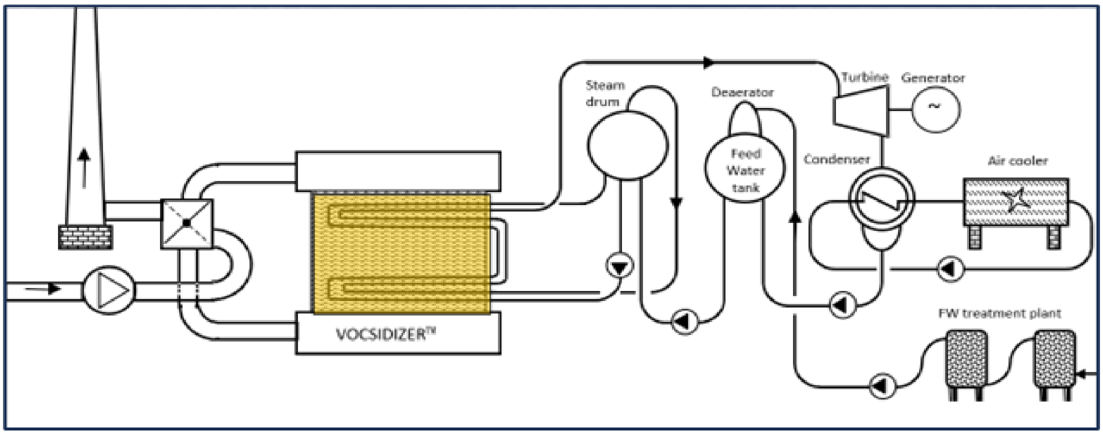

***Figure 9**: Principal Steam Cycle of VAM Power Plant WestVAMP, Australia (Courtesy of MEGTEC-Dürr)*

3.2.3 Electricity from a VAM Power Plant

For electric power generation VAM must be supplemented with drainage gas to ensure that a steady methane concentration is maintained and thus that the use of the turbine generating electricity is optimized. Using gas from the mine drainage system is a low-cost way to boost the energy content of VAM.

3.2.4 Tri-generation: Heating-Electricity-Cooling

If there is a need for cooling, e.g., to cool the workplace at a deep mine, an absorption chiller can be added to the cooling water cycle of a VAM Power Plant (see **Figure 10**).

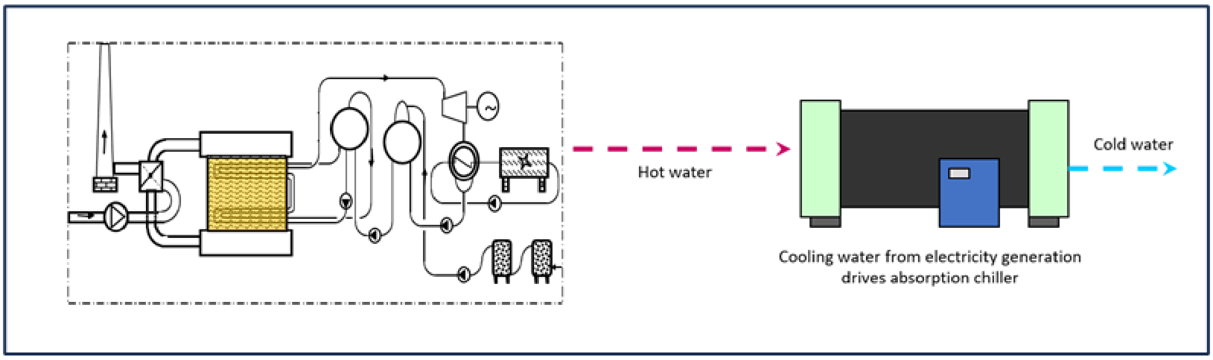

***Figure 10:** Cooling hot water from the VAM-based electricity generation drives an absorption chiller*

Cold water (at a temperature of typically 4 to 6 °C) can be brought down to the mine workings for cooling or sold for the same purpose to either nearby plants to support industrial processes, or buildings located in the mine's proximity. **Figure 11** illustrates an output from a VAM treatment installation at a coal mine where the emission rate and concentration of methane could sustain production of power and cooling for nearby industrial or commercial use. Adding cooling has a minor impact on the amount of usable power generated by recovering energy from what would otherwise go to waste and be a climate pollutant.

Example:

1,000,000 m3/h, 0.8% VAM → 70 MW (th) → 20 MW (el) → 18 MW (el) + 36 MW (cool)

***Figure 11**: Combining VAM* power *generation with cooling for nearby industrial or commercial use*

3.3 Optimizing variation of VAM and available drainage gas concentrations

Planning an integrated power production facility that incorporates conventional power production using internal combustion engines and a VAM treatment installation requires a full understanding of the quantities and concentrations of methane available for recovery and use. After assessing available methane, including VAM and drainage gas, it is important to evaluate the specific conditions such as efficiency and costs of gas engines, flares, and VAM processing infrastructure.

If, for example, a VAM Power Plant is considered, it is worthwhile evaluating the input of additional flows of drainage gas enriching the ventilation air, so that the additional concentrations above 0.2% necessary for maintaining the oxidation process, can be fully utilized (see **Figure 12**).

For a VAM mitigation plant with methane concentrations occasionally dropping below 0.2% it is important to ensure that drainage gas is made available for increasing concentration when necessary.

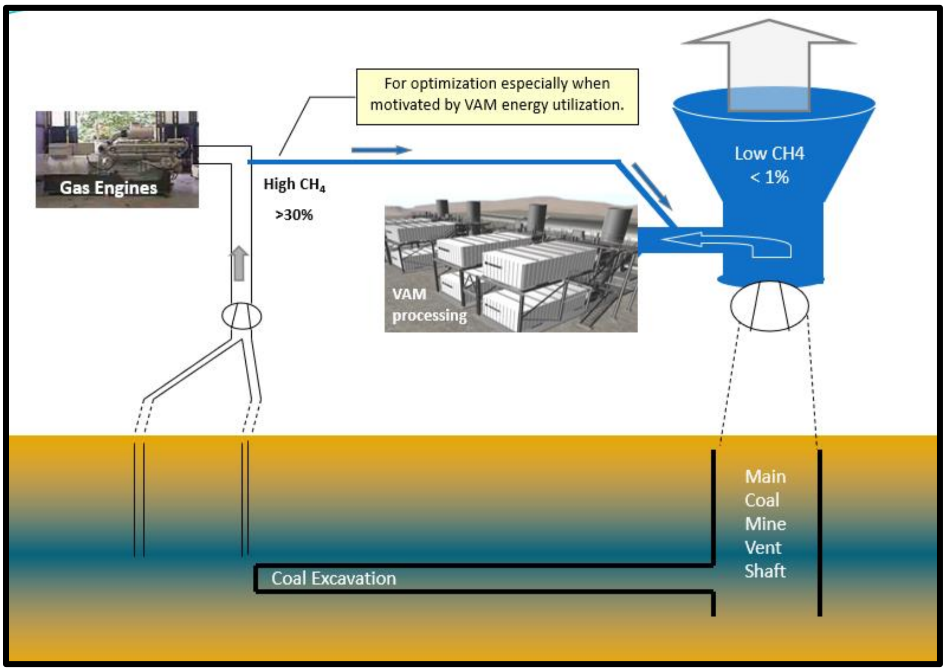

***Figure 12**: Overall optimization of methane from coal mine*

3.4 Conclusions on energy generation from VAM

- VAM treatment installations can be designed with embedded water/steam/oil-tubes to produce usable steam power and thermal energy production.
- If a large thermal user can be identified near the ventilation shaft of the coal mine, additional revenues can be captured by a project investor.
- Even if offsite sales are not possible, use of the produced energy for the mine's own purposes can be attractive.
- Heat provided from a VAM treatment installation can be used as a driving energy for an absorption chiller – e.g., for generating cold water (at 4°C to 6°C) that can be utilized for cooling equipment and personnel at the workings of a deep mine.
- If only a small market for thermal energy can be identified, a simple heat exchanger on the installation's hot exhaust could be sufficient to provide smaller quantities of energy for sale.
- For electric power generation, drainage gas can be used for balancing and, if necessary, for supplying additional methane to ventilation air when underground activities cause a temporary decrease in concentration. For security reasons, the degree of caution while designing and executing any procedure of supplementing VAM with additional methane flows, must be of the highest level.
- A single installation with the right conditions can provide "tri-generation" of electricity, heating, and cooling.

4. Guidelines and tools for applying VAM RTO technology

4.1 Lifetime of coal mine ventilation shaft

The lifetime of underground mining sites and their ventilation shafts are dependent on the extent of coal reserves, mining conditions, mining methods, and economics. At some mines, the main ventilation shaft can be kept in use for 10 to 15 years, or even more, whereas in others, the location of more local ventilation shafts, known as bleeder shafts, can be shifted more frequently, in some cases even as often as every 3 to 5 years.

4.2 Prospects of modularity and relocation

To reduce all the VAM emissions coming out from a shaft, a VAM mitigation plant needs to be able to process the full flow of ventilation air containing methane. Bearing in mind the already discussed very large volumes escaping from each shaft, the size of a full-size VAM installation, and thus also its CAPEX, are large. The expected lifetime of a ventilation shaft, as well as the anticipated methane concentrations, are therefore of vital importance, especially when the generation of electricity is being considered.

Certain RTOs can be designed so that they can be relocated, as can also be some of the major components of a VAM treatment plant such as ductwork, safety features, and dampers. As a result, for a coal field where several shaft locations are to be used over time, planning for relocation and reuse of some components of the installation is crucially important, as it directly impacts the project economics.

Regardless of whether a VAM treatment plant is an installation to generate electricity or is intended to serve as a tri-generation facility (combined cooling, heat, and power), the RTO portion of the system can be relatively quickly installed and made operational to start reducing the emissions, while the more complex components of the system can be installed later. Similarly, originally installed RTO units used only for mitigation purposes could be replaced by units with heat recovery later, thus allowing the former to be relocated to another site to serve either as temporary units (as in the previous case) or for mitigation purposes.

4.3 Indications of VAM RTO footprint

Ducting of the scale that is necessary to transport very large volumes of air ventilated from a mine is expensive, and therefore a VAM RTO processing plant should be installed as close to the évasé as possible. The RTO units are typically sized to process 50 to 120 thousand m^3/h of air, but their exact capacity varies based on the specific design offered by a supplier.

RTO processing units require a lot of space. However, single bed RTOs can be stacked and thus configured effectively. One possible configuration includes modules of 4 units arranged on two levels, forming a “VAM processing cube”, which is capable of processing 250 thousand m^3/h (see **Figure 13**).

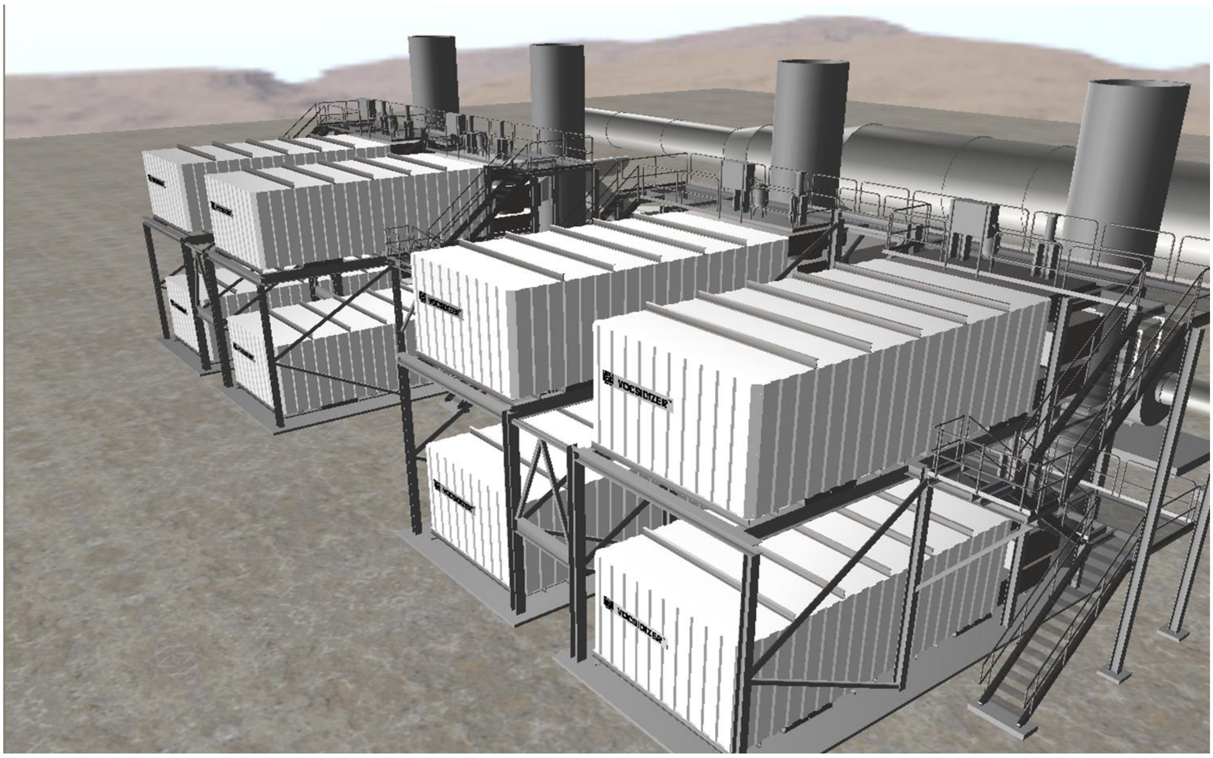

Figure 13*: Single bed RTOs stacked and arranged on 2 levels (Courtesy of MEGTEC-Dürr)*

In this example, the footprint of a VAM cube is some 13 m x 14 m. Process fans add around 3 m to the length, increasing the footprint to around 13 m x 17 m. The cubes can be freely arranged to fit the available terrain.

Two bed RTOs are too large to be stacked, but each unit can be sized to process a higher volume of air. A unit sized at 12 m x 24 m processes 100 thousand m^3/h, whereas a unit sized 15 m x 35 m processes 250 thousand m^3/h.

4.4 Finance

4.4.1 CAPEX

VAM RTO mitigation plants are air processing installations. Irrespective of methane concentration, all the air from which methane must be removed needs to pass through an RTO unit. Therefore, CAPEX (investment cost) per unit of mitigated methane varies. The higher the VAM concentration, the lower the cost per mitigated unit of methane.

When VAM concentrations become very low, the costs that are not related to the volume of the processed air, such as engineering, control systems, connection to the évasé, access roads etc., become more dominant, and therefore processing half of given volume can be expected to have a CAPEX being somewhat more than half the original calculation. Correspondingly, doubling the processing capacity can be expected to increase CAPEX a bit less than twofold (see cost indications at the end of this chapter), since the same costs (engineering etc.) do not double.

To sustain the oxidizing process inside the RTO, the energy input based on at least 0.2% methane concentration in ventilation air is required. If concentration is lower than 0.2%, then it is necessary to provide supplementary fuel/energy (a gas such as methane or propane, or energy in the form of electricity) to produce additional heat to keep the oxidation process going. This is typically the case in most industrial applications of RTO, as the energy of the pollutants coming into an RTO installation is often in low concentrations. However, from the perspective of VAM processing this does not make sense, as the huge air volumes involved would require adding large quantities of fuel/energy, thus making the whole process far too costly.

Therefore, while it is technically possible to design and manufacture an RTO that has self-sustaining oxidation at VAM concentrations below 0.2%, the high cost per mitigated methane unit effectively prevents such installations from practical application.

4.4.2 OPEX

The operating costs (OPEX) consist mainly of the cost of energy needed for the processing fans which pull ventilation air from the évasé to the RTOs, and the cost of the personnel required.

4.4.3 Financing costs

The third main cost component that needs to be considered is the financing cost of the project. It is determined by the cost of capital and the time over which that cost is to be distributed.

4.4.4 Financial feasibility

The financial feasibility of a potential VAM processing project needs to determine all relevant case-specific conditions and costs.

A critical determinant for a VAM treatment plant design is the average VAM concentration and its expected variation over time. As soon as a VAM processing project is considered, continuous measurement of the actual VAM concentrations should be initiated. Measurements made over a longer duration are more useful for design purposes as they are more likely to capture the long-term variability in gas concentration and provide the information necessary to optimize the design of the installation. See **Figure 5**.

If energy recovery and utilization are considered it is important to determine availability of drainage gas close to the VAM processing installation, to maintain the methane concentrations coming to the RTOs at a steady level. This is particularly important if VAM is to be used for electricity production, as a stable methane content is required for a steam turbine to run at optimal capacity. Plants designed to use energy for production of thermal energy for heating or cooling, are less sensitive to swings in methane concentration.

4.4.5 Indications of project costs and required support actions

For the purpose of this study, during the second half of 2023, cost information provided by suppliers of VAM RTO systems and by VAM RTO project developers, both with relevant experience in commercial size VAM processing, was compiled and evaluated. This led to the cost estimates for RTO-based VAM processing plants presented below[3].

The total investment cost (CAPEX) of a VAM processing plant for mitigating methane depends mostly on the volume of ventilation air to be processed. Methane concentration, while it has certain impact,

[3] Calculations were done with an assumption of no special conditions or complications (such as e.g., location of a plant in a mountainous area or an absence of sufficient power supply).

is not significant, to the point that for the first general assessment of CAPEX, it can be totally ignored. Based on the information obtained, it was found that under the nominal conditions CAPEX for a plant processing a ventilation airflow of 500 thousand m^3/h is around USD $14 million +/-15%.

For the Project Lifetime Cost, (ten years of) OPEX[4] and financing costs[5] are added, totaling around (14 + 10 x 1.2 + 8 =) USD $34 million.

A VAM processing plant consists of multiple RTO units, each processing a portion of the air flow. Doubling the air processing capacity requires doubling of the number of RTO units. The costs of some major items of an RTO VAM processing plant are rather linear, while other items barely change with size of the plant (see **section 4.4.1**). Therefore, it can be assumed that processing half the volume discussed above, i.e., 250 thousand m^3/h, would cost slightly more than half of the indicated price and amount to roughly USD $8 million (+/-15%). Similarly, processing twice the initial volume, i.e., 1 million m^3/h, would cost a bit less than twice the original price i.e., USD $25 million (+/-15%). Please note that these are approximate indications intended to give merely the first assessments of the potential cost of a VAM processing plant (see **Figure 14**).

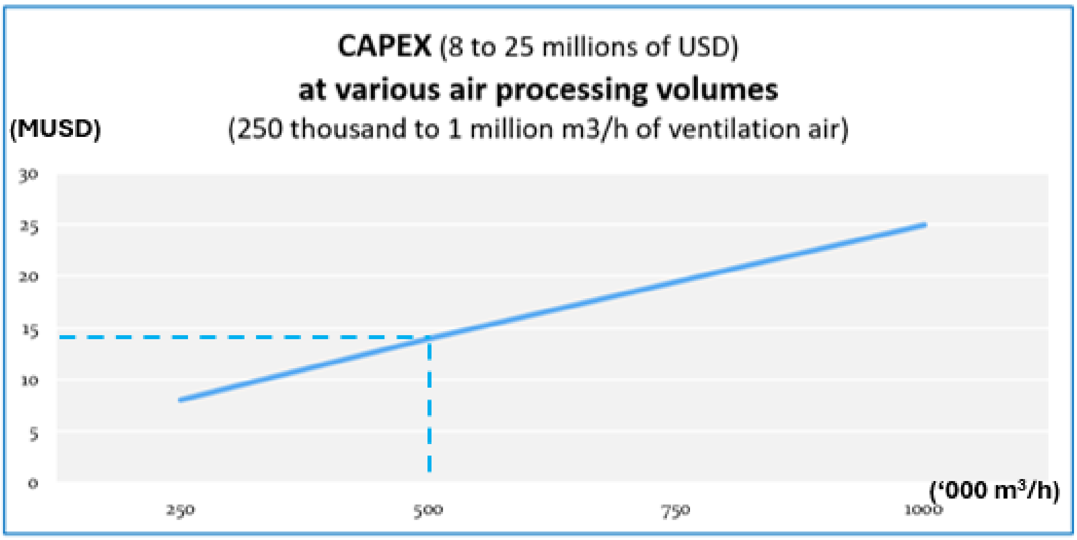

***Figure 14**: CAPEX as total investment cost for VAM mitigation plants of different sizes*

Detailed cost estimates for a specific VAM processing installation must be based on thorough feasibility studies[6] using data that represents actual site conditions (e.g., long-term relevant VAM and drainage gas measurements) and including input from experienced VAM RTO system suppliers.

Taking again the example of the plant processing 500 thousand m^3/h of ventilation air containing 0.5% methane, it can be expected that such installation would annually mitigate methane corresponding to 400 thousand tCO_2e (see table based on 100-years of comparison, with GWP=30 in **Figure 19**). Assuming that the project is based on a 10-year lifetime, its total cost, as calculated above, would be

[4] Assuming OPEX of USD 1.2 million per year, based on USD 100 per MWh.
[5] Assuming 12% interest rate and straight amortization over 10 years (note high interest rate).
[6] Feasibility study needs to determine e.g., site conditions, fan volume rate and concentration of methane in the ventilation air, size and type of évasé, altitude of proposed site (affects air density and impact requirement on fan power), sizing of a VAM treatment plant, cost of power, availability of carbon credits and/or other incentives, financial requirements and funding sources, etc.

USD $34 million, and the number of emission reduction credits would total 4 million tCO_2e (400 thousand per year over 10 years), which gives a cost per tCO_2e of around USD $8.5 (by dividing USD 34 million by 4 million tCO_2e).

Since the cost of a VAM mitigation plant is all about the volume of air being processed, the methane content in the ventilation air to be processed is a key factor determining the revenue and thus also the profitability of the plant. A plant processing VAM concentration of 0.2% will have a total cost per mitigated tCO_2e around USD $20. If the concentration grows to 0.3% the cost will decrease to USD $14, and fall further down to USD $6, provided that the methane concentration reaches 0.8% (see **Figure 15**).

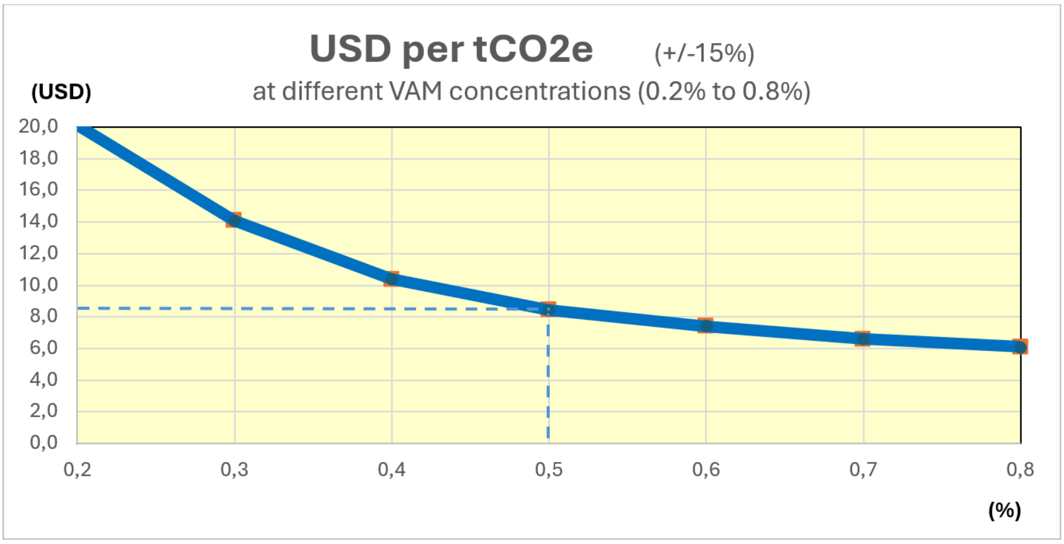

***Figure 15**: Total cost of RTO VAM processing plant at different VAM concentrations*

USD $20 per tCO_2e

With the above calculations in mind, primary focus should be given to mitigating emissions of at least 0.4% methane concentrations. This is because to stimulate investments in VAM processing, emission reductions need to have a value of minimum 2-3 times more than the cost (per tCO_2e) of mitigation. With the latter at the level of USD $10 (corresponding with 0.4% concentrations), a value of USD $20 per avoided tCO_2e secured over the first 4-5 years of a plant's operation should be sufficient to attract the necessary investments, by the mine itself or by third party investors. Whether this value is a revenue in the form of Carbon Emission Reduction Credits or a penalty for the remaining emissions it does not influence the calculation, and its outcome remains the same. After the initial period of 4-5 years (once the CAPEX has been paid back), it is likely that substantially lower values, at the level of USD $10 per tCO_2e or even less, will be sufficient to motivate continued operation of a VAM mitigation plant.

Supporting starting up of VAM mitigation projects

If a value can be attributed to the reduction of methane emissions (in the form of avoided penalties or revenues for emissions reductions as discussed above), VAM might become economically attractive and thus more popular.

A government or a climate fund wanting to support initiation of VAM mitigation projects should focus on securing a value of no less than USD $20 per tCO_2e for at least 4-5 first years of the project's operation. Thereafter, once the CAPEX has been paid back (and a government/carbon fund has secured emission reduction at a competitive price), the project could be brought under the local carbon trading scheme, provided that the latter exists in a given jurisdiction and has a methodology for accounting VAM emissions.

If that is not the case, a lower value ranging between USD \$5 to \$10 per tCO_2e, should still be guaranteed for the rest of the project lifetime, to sufficiently cover OPEX, and thus provide an investor with a sufficient incentive to maintain operation of the VAM mitigation plant until a higher value for the emission reduction can be obtained.

Such approach would provide:

1. The financial drivers required for VAM mitigation projects to happen, and
2. Access (for actors in the carbon emission market) to inexpensive carbon emission reductions.

Emission reduction cost comparison

The above results can be compared to the prevailing cost estimates for Carbon Capture and Storage (CCS), which indicate a range of USD \$100-\$150 per tCO_2e. It is also worth noting that CCS technology is still in the early stages of commercialization. Once it matures and begins to be applied on a commercial scale, it is possible that the best suited storage sites will be relatively quickly exploited, which would then lead to a further cost increase.

Ventilation shaft longevity and concept of modularity

The average lifetime of a mine ventilation shaft varies depending on the region (see **section 4.1**) as active mining development gradually progresses away from the ventilation infrastructure. Therefore, mining companies need to periodically construct new ventilation shafts. Cost effectiveness of VAM processing facilities can be improved by introducing a residual value through modular design of components that can be relocated across sites and companies.

4.5 Eight steps to prepare for a VAM project

According to a model developed for the purpose of this paper[7], there are 8 steps that need to be considered before successfully launching a VAM processing project (see **Figure 16**). The steps can be seen as covering three basic areas:

- Internal information on essential basics: Resource assessment of the VAM, including historic emissions and future projections of methane concentration in the ventilation air based on mine plans and coal extraction rate, the expected ventilation air volume per hour, as well as VAM plant's location, and availability of drainage gas that can be allocated to it.
- External information on the potential value of emission reduction in the jurisdiction where project is to be developed, and on the newest global VAM-related technologies, practices, and developments.
- Potential partners that could be involved in financing, in project development, and as VAM processing system suppliers.

[7] By RM Business Consulting AB

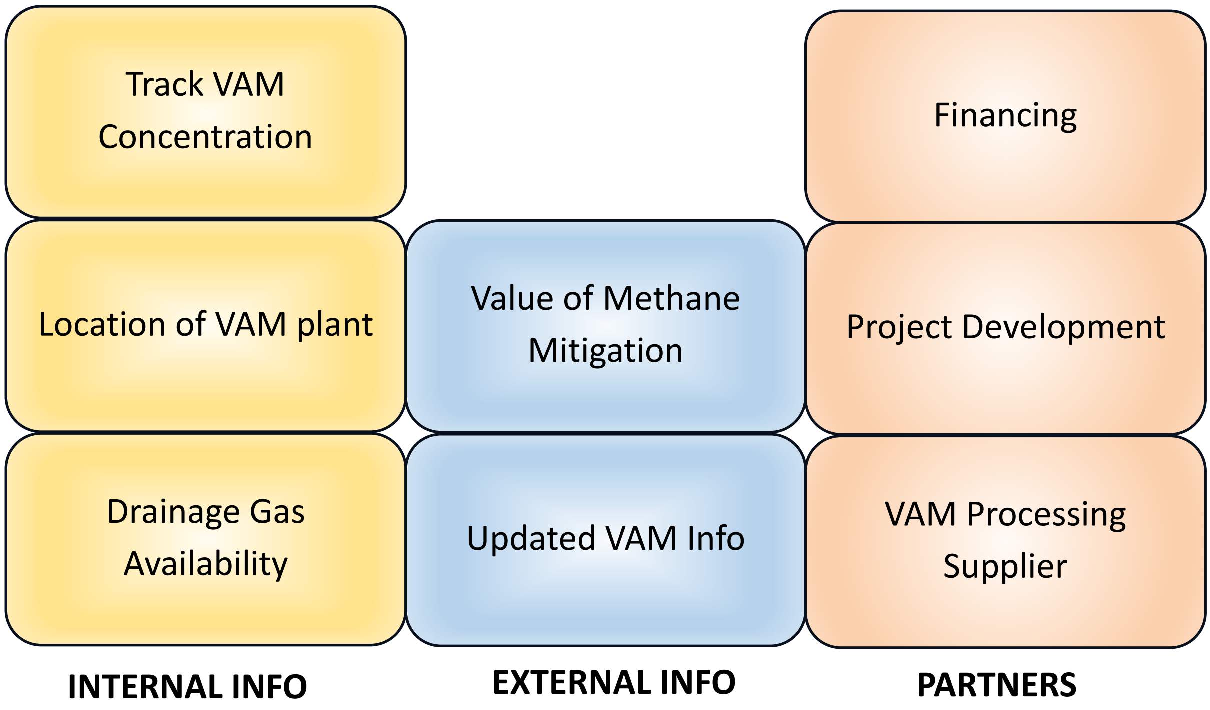

***Figure 16**: 8 Step Model for launching a VAM project*

The 8 steps are as follows:

1. Track VAM concentration

When considering a VAM processing installation, the first thing to do is to secure reliable tracking of the relevant VAM concentrations over as long a period of time as possible. It is necessary for taking educated decisions on the actual design of the forthcoming VAM plant.

2. Identify the location of the VAM plant

Examine the possibilities for locating a VAM mitigation plant in the vicinity of the évasé (the mine ventilation shaft) targeted for the project, using the indications of footprint discussed in **Chapter 4.3**. Review future mining plans to determine the expected longevity of the considered VAM mitigation plant.

3. Access Drainage Gas Availability

Determine the possibility of providing sufficient drainage gas for injection into the ventilation air prior to the point of processing to either balance VAM concentration at a steady level (if power generation is considered) or sweeten the energy level of the system and thus increase the amount of mitigated methane emissions.

4. Evaluate Emission Mitigation Value

Determine the range in volume and value of methane emission reduction (resulting from the expected carbon credits, carbon offsets, or avoided penalties) that can be attributed to the VAM project, especially for the first 4-5 years of its operation.

5. Secure Financing

Determine who should be the investor, whether the mine operator, or a third party, and secure the financing of the project.

6. Select a Project Developer

Determine who should be a project developer, whether the mine operator or a third party.

7. Choose a VAM Processing System Supplier

Explore potential VAM processing system supplier, be it:

- An RTO supplier with successful, long-term VAM processing experience.
- An RTO supplier with sufficient experience acquired from other relevant industrial applications.
- A supplier venturing a technology under development, looking for a suitable site for large scale demonstration.

8. Stay updated on VAM Technology and Global Developments

Be updated on the global status of VAM processing. More information on projects and technology demonstrations related to coal mine methane and VAM processing can be obtained e.g. from:

- The UNECE Group of Experts on Coal Mine Methane and Just Transition (https://unece.org/sustainable-energy/just-energy-transition/group-experts-coal-mine-methane-and-just-transition), and
- The GMI Coal Subcommittee (https://www.globalmethane.org/coal/).

5. Safety of RTO VAM Processing Installations

With a long history of deadly incidents and coal mining disasters worldwide caused by methane, coal miners are trained to be cautious with any new methane-related infrastructure or technology and pay close attention to any inherent risks.

5.1 Staying clear of explosive range of methane concentration

An RTO is not designed to handle an explosive range of gas (in methane's case between 5% and 15%) Designing ductwork for RTO that could handle the effects of a potential explosion would require dimensions and use of components like that which are used in construction of heavy-duty steam vessels. Even in such cases, however, the installations would likely still be unsafe, and on top of it extremely expensive. In addition, due to the huge dimensions of the ductwork handling mine ventilation air, it is very difficult (or impossible) to equip it with flame arrestors and rupture disks that would activate if an incident led to a methane ignition. Instead, focus should be on measures to avoid coming close to explosive range concentrations.

Since in industries in which application of RTOs is typical, be it chemical, petrochemical, pharmaceutical, etc., it is common that gas mixtures of the processed flow incidentally fall within the explosive range. Experienced RTO suppliers are therefore well familiar with the danger that the occurrence of hazardous methane concentrations in the ventilation air poses to the mine and miners working underground. They also have knowledge of the full range of preventive measures for ensuring the safety of VAM processing installations. The implementation of specific measures is determined by local mining conditions and regulations, and may include any of the following:

- Multiple LEL (Lower Explosion Limit) measurements with adequate redundancy,
- The ability to add fresh air to further dilute methane in ventilation air if its concentration becomes even slightly higher than normally recorded,
- Ability for ventilation air flow to be diverted to bypass the RTO if methane concentration exceeds the set point concentration,
- Capacity to purge the system with fresh air to avoid methane concentration build up,
- Maintaining an open gap in the duct work between the VAM processing system and the mine's évasé.
- Employment of spark avoidance measures in ductwork connected to ventilation air flow; and
- Designing ductwork to avoid flammable dust build up.

The lower explosion limit, LEL, is defined (ISO 10156) as being 5% and is related to ambient air (at 20^{o}C and the sea-level pressure). In Europe, some margin is included, lowering the LEL to 4.4% (IEC 60079). With the typical design, a VAM RTO installation operates at no more than 25% of LEL (i.e., methane concentration at the level of 1.1 to 1.25%). This is the maximum level going into RTO units. Often the limit is set by system suppliers or by customers to be lower, be it 1.0% or even 0.7%. On top of it, all relevant national/regional guidelines and limits always need to be considered and respected.

The system is equipped with sensors that detect any concentration exceeding the acceptable limit, and in case of such occurrence, it immediately isolates the RTOs and sets the mine ventilation to a bypass mode.

5.2 Avoiding pressure pulses

Physically, VAM RTO processing installations are located on the surface. It is important that their connection to the mine ventilation shaft, the évasé, is designed and installed in such a way that in case of any disturbances at the VAM processing installation which could potentially impact the mine ventilation air flow, VAM is diverted and allowed to be released directly into the atmosphere. Such practice is standard for experienced RTO suppliers, as the typical complex RTO installations in the industry are characterized by great flexibility allowing them to switch multiple unrelated process lines on and off without disrupting coal production.

5.3 Dust control

Coal dust in ventilation air can build-up and thus increase potential risk of clogging and ignition. Fine dust filters, however, would cause a pressure drop and be very expensive for handling typical ventilation air volumes. One solution is to design measures that lower the velocity of dust particles, allowing them to settle either in low points of the ductwork system, or in collection pockets, from where they could be regularly removed. Fine dust particles that are difficult to drop out of the air flows do not present a challenge to a typical RTO, as they are carried all the way to the hot zone, where they are safely combusted.

Besides coal, the ventilation air can also contain other dust components that need to be controlled. Dust particles consisting of silica or calcium compounds may have a destructive impact on the RTO’s beds and must be accommodated by the installation’s interior design.

5.4 Addressing other safety concerns

If the provided by the supplier preventive actions to avoid the occurrence of explosive range of a gas mixture reaching an RTO are deemed (e.g., by the concerned mine’s management or personnel) not to be sufficient to ensure safe operation, additional actions should be considered. Operators should consult with their country's safety organizations for additional safety requirements related to installation and coupling RTOs to shafts.

6. Global Warming and VAM mitigation

6.1 Sources of anthropogenic emissions of methane

Even though by volume CO_2 is the most important greenhouse gas, methane has also a very significant environmental impact, resulting from its strong capacity to retain heat in the atmosphere. In addition, due to its short lifetime, its potency decreases over time, and therefore major reductions of methane emissions have an immediate and powerful positive effect on global warming (see **Annex 4**).

Methane emissions attributed to human activities come in principle from agriculture (mostly from livestock and manure), oil and gas industry, coal mining, biogas generation, landfills, and wastewater treatment (see **Figure 17**).

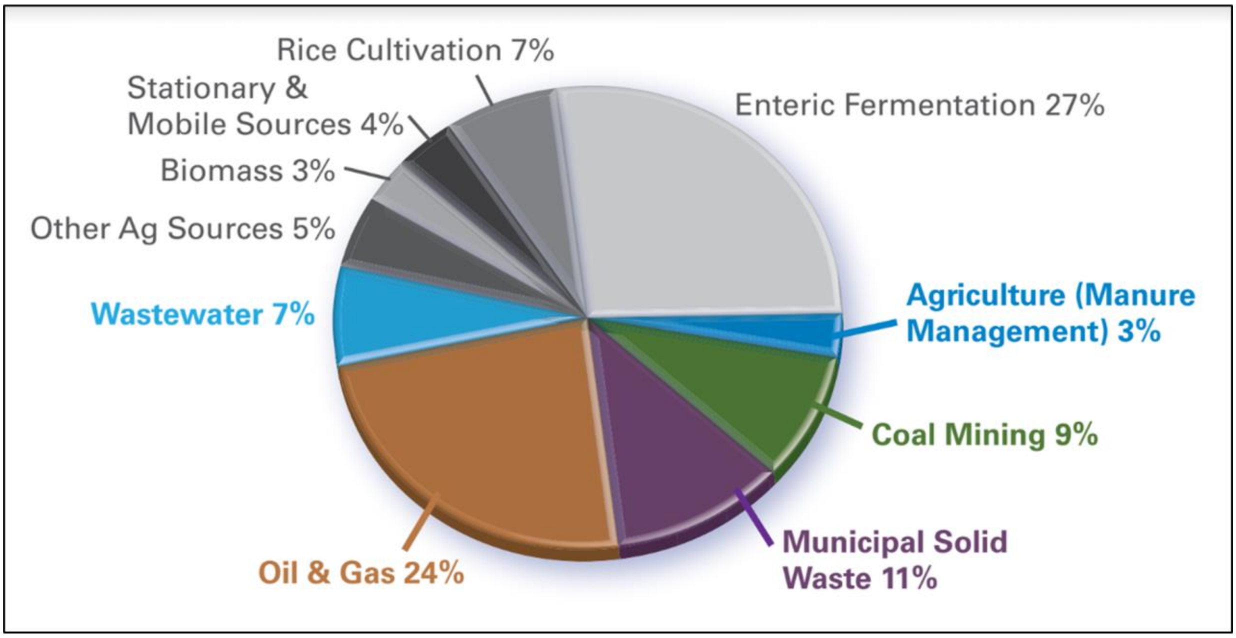

***Figure 17**: Estimated global anthropogenic methane emissions by source in 2020* (Courtesy of Global Methane Initiative)

Even though coal mining represents less than 10% of anthropogenic methane emissions, the size of many of the emission sources in that category gives coal mine methane particular significance in terms of facility of its detection, capture, and treatment.

6.2 VAM from a climate perspective

A major issue is that anthropogenic methane emissions are often diffused, coming from very many small single sources. For instance, a single cow, according to the United States Environmental Protection Agency (US EPA), emits on average between 60 and 120 kg of methane annually. As a result, any sort of emission control from livestock is very difficult. Instead, in that sector efforts are being made to develop forage that leads animals to lower methane generation.

What makes VAM a very interesting case from methane mitigation perspective is that its emissions are not only large in volume, but also concentrated to one point of emission, and thus easy to process.

A large coal mine ventilation shaft might emit approx. 50,000 tonnes of methane annually, which corresponds to the emissions generated by 400 to 800 thousand cows.

Taking a different reference point, methane emissions from a large coal mine ventilation shaft, expressed in CO_2e calculated using GWP_{20}, have the same contribution to global warming as 2 million cars, or a coal fired power plant of 500 MWe (see **Figure 18**; for more details on these calculations, as well as comparison with methane emissions from cows, see **Annex 1**).

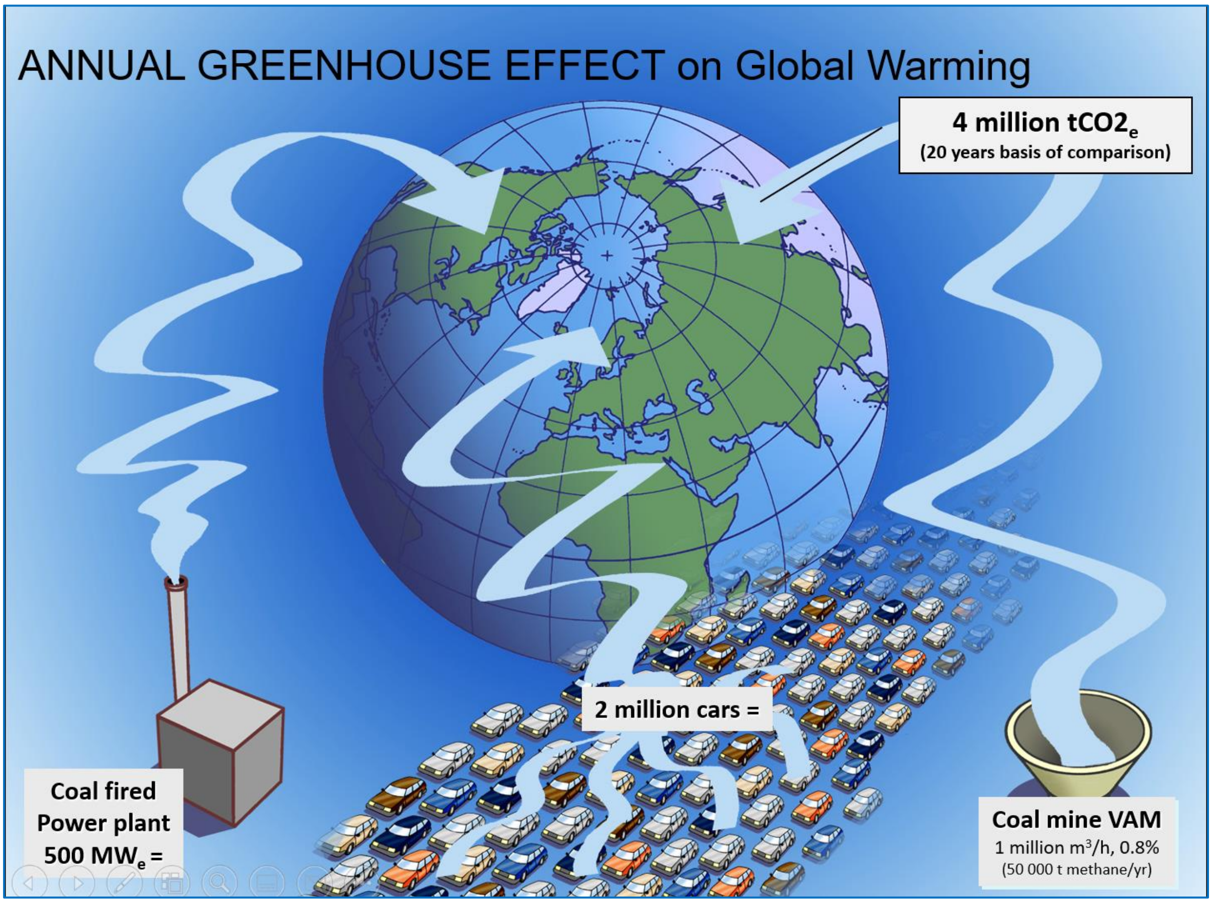

***Figure 18**: Global Warming impact comparison (on a 20-year basis) between emissions from VAM (methane), cars (CO_2), and a coal-fired power plant (CO_2)*

6.3 VAM emission mitigation achievements

GHG emission reduction results are presented in tCO_2e, i.e., metric tonnes of CO_2 equivalent, using a conversion factor provided by the Intergovernmental Panel on Climate Change (IPCC).

For many years, GHG emission reduction projects were considered successful even if their record showed reductions as low as 30 thousand tCO_2e. It is because at that time any emission reductions were considered of value.

Now in the 2020's, the situation has started to change. As the number of projects significantly grew, the focus and recognition started to be given to projects achieving major emission reductions, and thus making a real difference. Large VAM emission reduction efforts fall into that category.

The table shown in **Figure 19** indicates the level of approximated emission reductions in thousands of tCO_2e[8] that VAM projects can be expected to achieve, depending on the volumes of ventilation air that is to be processed and its methane content. The calculations use GWP_{100} (i.e., the multiplier relative to CO_2 on a 100-year basis) of 30 and their results are rounded. The table should be used to calculate the expected emission reductions as a base for the anticipated revenues or avoided penalties.

VAM concentrations / Ventilation air volumes (m^3/h)	0.25%	0.5%	0.75%	1%
250,000	100	200	300	400
500,000	200	400	600	800
1,000,000	400	800	1 200	1 600

***Figure 19**: Expected results of VAM mitigation in thousand tCO_2e (using GWP_{100} of 30)*

Figure 20 indicates, in turn, the expected results using GWP_{20} (i.e., the multiplier relative to CO_2 on a 20-year basis) of 82. The table should be used to evaluate the actual near-time effect of a VAM mitigation project on global warming and climate change. As in the previous case, the presented numbers are rounded.

VAM concentrations / Ventilation air volumes (m^3/h)	0.25%	0.5%	0.75%	1%
250,000	300	550	800	1100
500,000	600	1100	1600	2200
1,000,000	1100	2200	3300	4400

***Figure 20**: Expected results of VAM mitigation in thousand tCO_2e (GWP_{20} of 82)*

[8] Each value is calculated using the following formula, and adjusting air volume and VAM concentration: Cleaning Efficiency (98%) x Availability (96%) x Total hours in a year (24x365) x Air Volume (Ventilation air per hour, from 250 thousand to 1 million m^3) x VAM concentration (from 0.25% to 1.0%) x [GWP (30 or 82, respectively) x Density (0,71) - CO_2 result emitted from RTO oxidation (1.95)] / 1000

7. Global emission reduction commitments

7.1 Kyoto Protocol, Paris Agreement, and Global Methane Pledge

The Kyoto Protocol (1997) introduced a global system of attributing a monetary value to reducing GHG emissions through carbon credit trading. The trading system was launched in 2006 with the regulations valid for the period 2008-2012. The Protocol was signed by 192 countries. However, during the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen (2009), efforts to extend the Kyoto Protocol and unify emerging carbon markets failed, leading to a significant drop in carbon credit values. Despite this, local emission reduction schemes and carbon markets continued to evolve and eventually rebounded in the following decade.

In 2015, the Paris Agreement was signed by 196 countries with the goal of limiting global warming to well below 2°C, and ideally below 1.5°C, to avoid catastrophic climate impacts. This agreement marked a critical shift in global climate policy, emphasizing long-term commitments for emission reductions across all sectors.

In 2021, a specific commitment to reduce methane emissions was launched, namely the Global Methane Pledge. It has been signed by 159 states and the EU as of end of 2024. This pledge specifically targets methane, a potent greenhouse gas that has a much stronger short-term warming effect than CO_2, making its reduction a crucial strategy for mitigating near-term climate change.

While the world has made significant commitments to reduce GHG emissions, the focus now must shift from promises to action. To achieve meaningful climate progress, efforts should prioritize large, concentrated, and easy to detect and capture emissions of GHGs that can deliver immediate reductions. Ventilation Air Methane (VAM) emissions, as seen in coal mines, represent one of the most significant and easily mitigated sources of methane, making VAM an ideal target for swift and impactful action in the fight against global warming.

7.2 Urgency of taking action

The main cause of global warming and climate change is that carbon that was taken out of the carbon cycle 300 million years ago is being retrieved from the deposits of coal, oil, and natural gas, and reintroduced to the present-day carbon cycle. Its supply from both natural and anthropogenic sources greatly exceeds the ecosystem's absorption capacity, thus increasing the atmospheric content of the GHGs, particularly CO_2 and methane. Despite all the commitments to reduce GHG emissions, in 2022 their level was higher than ever.

Figure 21 illustrates the development of global energy production and the mix of energy sources between the years 1990 and 2021. It shows that fossil-based energy overall still constitutes around 80% and the total, and that approximately 30% of the total comes from coal. As a result, it is safe to say that a phase out of coal-based energy will take time, especially that many new coal mines and coal-fired power plants are being built, particularly in the developing world. Furthermore, even though there are pilot projects and demonstrations of developing carbon free stainless steel production facilities, metallurgical coal (met coal/coking coal for production of steel) can be expected to remain in use even longer than thermal coal. Therefore, if coal is mined, regardless of what its end use is to be, the continuous VAM emissions associated with it should be mitigated to protect the planet.

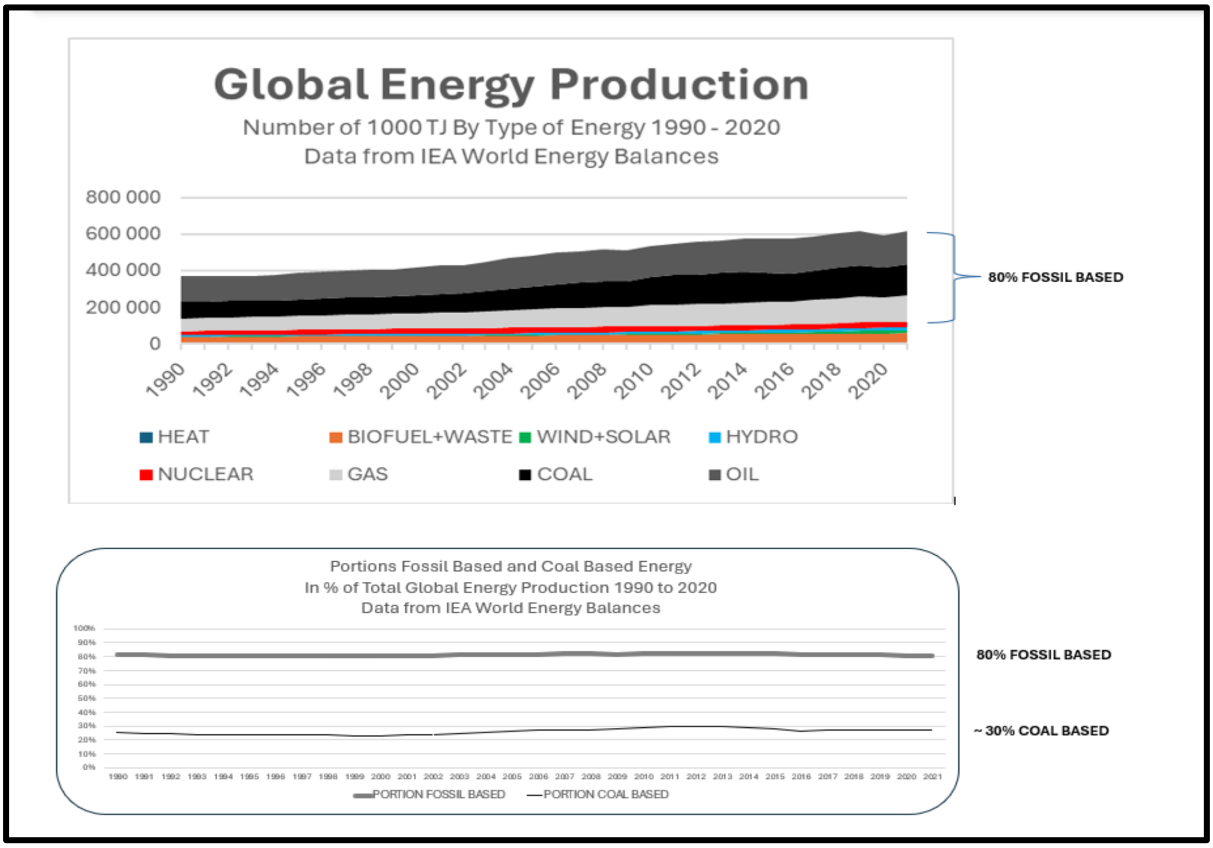

***Figure 21**: Global Energy Production*

7.3 VAM mitigation and carbon credits

Given that efficient VAM mitigation technology was proven by the end of the first decade of the 21st century, and the immediate and powerful positive effect that VAM processing has on global warming, one would expect that by now there were hundreds of VAM processing installations developed worldwide. However, that is, unfortunately, not the case.

As VAM processing is a costly investment, its development depends on a value attributed to methane emission reductions. When the emerging markets of carbon credits trading slowed down at the end of 2009, that caused uncertainty among the potential investors and impeded a wide-scale application of VAM technology.

There is a clear link between VAM processing development and application, and the prevailing mood of international climate conferences (see **Annex 5**). When the Paris Agreement was adopted in 2015, indicating its objective to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels”[9], new hope was injected to the markets of GHG emission reduction. Carbon trading started to increase again, both in volumes and in price levels.

[9] Paris Agreement Art. 2, available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf

The launch of the Global Methane Pledge in 2021, further underscored the importance of quickly reducing major emissions of methane. In the same year the International Methane Emissions Observatory (IMEO) was launched, to monitor and coordinate measurement of large methane emissions to the atmosphere, using ever more prevalent and accurate satellite technologies. In general, since the early 2020s, there is a renewed and increasing interest in VAM processing.

For more information on carbon credits trading schemes and the relation between development of carbon credits schemes and VAM processing see **Annex 5**.

7.4 Conclusions

Among the various climate change mitigation actions, Ventilation Air Methane (VAM) mitigation is highly cost-efficient. However, it faces significant resistance in terms of perception. Many politicians and media outlets hesitate to support it, fearing it could be used as a form of "greenwashing" by the coal industry, potentially prolonging the use of coal. Yet, the facts contradict this concern.

There is no doubt that the world must transition away from fossil fuels (coal, oil, and gas) for energy production as soon as sustainable energy sources can fully replace them. Realistically, however, coal mining is likely to persist for decades, releasing substantial amounts of methane, primarily in the form of VAM. Therefore, mitigating these emissions using commercially proven technologies is essential to reducing the harmful impact they would have on global warming and climate change if left to vent into the atmosphere.

When compared to other climate change mitigation actions, reducing large methane emissions offers the advantage of an immediate, powerful impact – critical for "buying time" until more significant reductions of CO_2 emissions take effect.

In this sense, VAM mitigation is a low-hanging fruit, offering a practical and timely solution to a pressing problem.

***Figure 22**: VAM Mitigation as low-hanging fruit*

ANNEX 1 - Global warming effects of a large VAM emission source compared to other sources

VAM emissions from major coal mine ventilation shaft

A large ventilation shaft, emitting 1 million m^3/h of air with 0.8% VAM concentration annually emits around 50,000 tonnes of methane.

Large shaft VAM emissions compared to a <u>number of cows</u>

According to US EPA, a single cow emits annually 60 to 120 kg of methane.

<u>Therefore:</u>

50 thousand tonnes of methane (average annual VAM emission from a large coal mine ventilation shaft) corresponds to emissions generated by 400 to 800 thousand cows.

Large shaft VAM emissions compared to a <u>coal-fired power plant</u>

- According to US EIA (Energy Information Administration), a coal-fired power plant emits 2.3 pounds (lb) of CO_2 per kWh (electricity). This equals 1.04 kg CO_2 per kWh.
- Compared on a 20-year basis, a tonne of methane in the atmosphere has, according to IPCC (Assessment Report #6 dated 2022), an impact on global warming 82 times greater than a tonne of CO_2.
- An efficiently utilized power plant can be assumed to have 90% availability.
- 50,000*82/1.04/(24*365*0.90) = 500 MW(e)

<u>Therefore:</u>

Mitigating VAM emissions from a major coal mine ventilation shaft has an impact on global warming (compared on a 20-year basis) similar to that of closing down a coal-fired power plant generating 500 MW(e).

Large shaft VAM emissions compared to a <u>number of cars</u>

- A car's combustion engine emits CO_2.
- Assuming an average emission of 150g CO_2 per km and an average annual milage of 14,000 km, a passenger car emits around 2.1 tonnes CO_2 per year.
- According to IPCC (Assessment Report #6 dated 2022), compared on a 20-year basis, a tonne of methane in the atmosphere has (on average) an impact on global warming 82 times greater than a tonne of CO_2. Consequently, taken on a 20-year basis, 1 million m^3/h of ventilation air with 0.8% methane translates into 4.1 million tonnes of CO_2e annually (on a 100-year basis, the corresponding amount is 1.5 million tonnes).

<u>Therefore:</u>

Annual VAM emissions converted into CO_2e correspond to those generated over a year by either 2 million cars (4.1 million tonnes of CO_2e) or 700 thousand cars (1.5 million tonnes of CO_2e), using respectively a 20- and a 100-year methane to CO_2 GWP ratio.

ANNEX 2 - Three basic types of RTOs

Regenerative Thermal Oxidizers (RTOs) were developed in the 1970s to handle industrial emissions to air of Volatile Organic Compounds (VOCs). The technology has been frequently used and optimized in efficiency and reliability. Ever since the early 1970s, RTOs have been applied in many industrial applications, including those of very low energy content. In such cases, some fuel gas needs to be added to the air fed to the RTO to maintain the oxidizing process. Natural gas, which consists mostly of methane (but which develops less energy than methane when oxidized), is commonly used as fuel gas. Over the years, RTO technology has been developed to suit several process applications, including mine ventilation air treatment.

All RTOs operate based on a very efficient heat transfer from the hot bed material around the center of the bed to the incoming air, and the controlled oxidation of the pollutants, whereby heating energy is released to the RTO's ceramic bed material, cooling the air that continues to flow through the RTO.

There are three types of RTOs: (1) single bed RTOs, (2) twin bed RTOs, and (3) multiple bed RTOs. The regular industrial RTO is of twin-bed category. It has two ceramic beds and a combustion chamber in between them. In a single bed RTO, there is no combustion chamber, but instead, the oxidation takes place inside of the ceramic bed. In a multiple bed RTO, there are more than two ceramic beds.

Single bed RTO

In a single bed RTO, the centre of the ceramic bed is heated by electrical elements (like a huge toaster) to as much as 1000^{o}C. Then the electricity is turned off and the ventilation air is passed through it picking up its heat. The air heats up to the point of oxidation of methane, i.e. ~850^{o}C, and then, as it continues to pass through and out of the bed, it releases the heat and efficiently transfers it back to the bed material. To avoid pushing the heat profile out of the exit side of the bed, the direction of the flow is reversed every few minutes. In that way, the heat profile is maintained in the center of the RTO.

If an air flow contains enough methane to maintain the oxidation process (i.e. 0.2%) and the incoming air is at ambient temperature of approx. 20^{o}C, the air flow leaving the bed (having passed through the center section heated to around 1000^{o}C) will have a temperature of around 60^{oC}.

The air flows in a single bed RTO are illustrated by the images in **Figure A-II 1**. Examples of industrial installations of single bed RTOs are shown in **Figure A-II 2**.

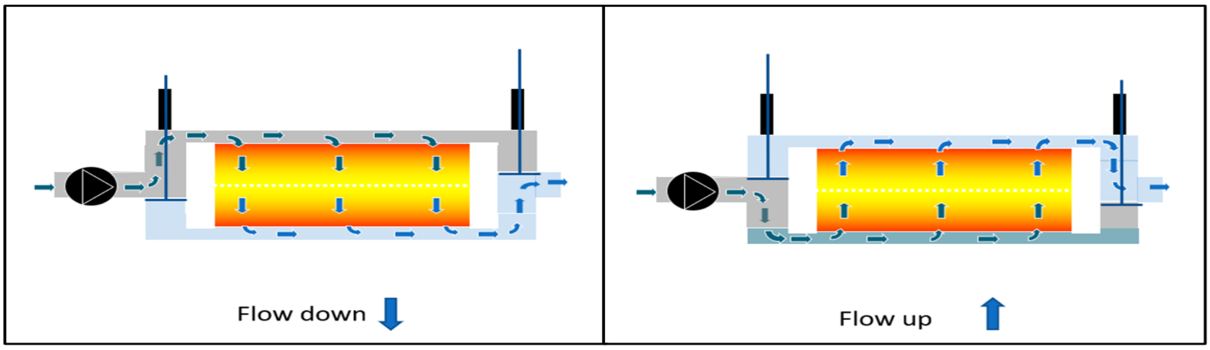

***Figure A-II 1**: Flows and heat transfers in a single bed RTO*

Figure A-II 2*: Industrial installations of single bed RTOs (Courtesy of MEGTEC-Dürr)*

Twin bed RTO

A twin bed RTO looks as if a single bed RTO was opened and half of its ceramic bed were flipped over, thus creating a void in between the two beds resulting from such procedure. That void forms a combustion chamber where the oxidation takes place. The heat transfer occurs in the same way as in the single bed RTO, but the process might appear clearer, as the air picks up the heat in the incoming bed and leaves it in the outgoing one.

The cleaning efficiency of single bed and twin bed RTOs are very similar. Most RTO producers guarantee 97% cleaning efficiency for both (undertaking special efforts it is technically possible to reach even 99%). What prevents a 100% efficiency is the fact that the air volume that is on its way into the bed when the flow is reversed (which occurs every few minutes), is backed out of the bed and that small volume of untreated air is typically released to the atmosphere.

Twin bed RTO is illustrated in **Figure A-II 3**. Examples of industrial installations of twin bed RTOs are shown in **Figure A-II 4**.

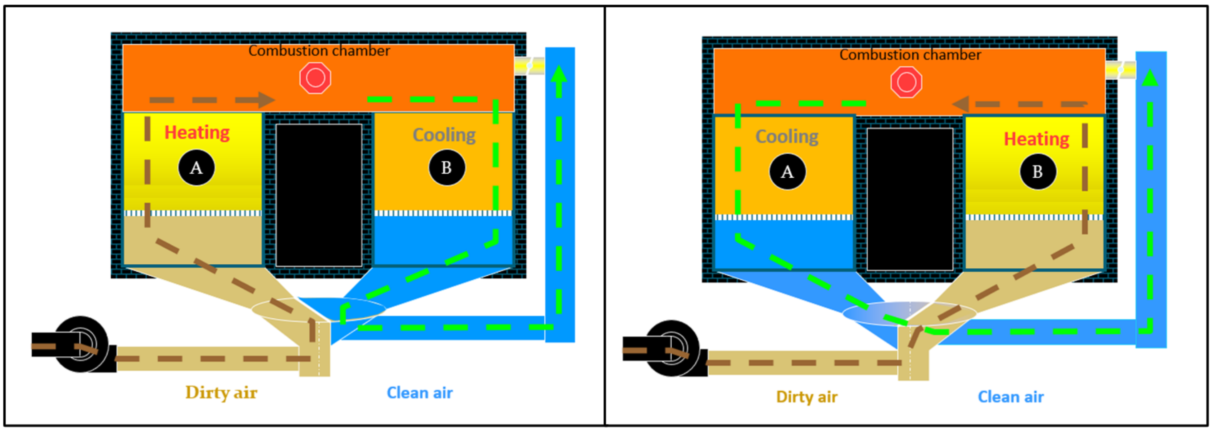

Figure A-II 3*: Flows and heat transfers in a twin bed RTO*

Figure A-II 4*: Images of industrial installations of twin bed RTOs (Courtesy of Anguil, Biothermica, and MEGTEC-Dürr)*

Multiple bed RTO

Multiple bed RTOs are typically used only in extreme industrial emission control cases, when the pollutant is either extremely toxic or has a very bad odor. A third (forth, or even fifth) bed allows to further improve the cleaning efficiency by catching the small volume of air that would otherwise be released to the atmosphere when the flow is reversed (see explanation above) and bleeding it into the air flow going to the hot zone of a different bed. On multiple bed RTOs, most producers guarantee cleaning efficiency at the level exceeding 99%. While it is technically possible to reach almost perfect efficiency of 99.9%, provision of each additional bed is very costly and thus does not have financial justification when it comes to VAM processing (in general, 95 to 99% - typically 98% - is deemed as acceptable/sufficient).

Rotary RTO

There is a system called Rotary RTO, consisting of a large, sectioned ceramic 8 to 12 chamber bed with a continuous operated rotary valve with one drive distributing the flow over the sections. This has the potential of obtaining high destruction efficiency, high availability and low maintenance. Additionally, there is basically no consumption of compressed air, and the pressure fluctuations are typically lower than for 2 or 3 bed systems.

Potential future development of VAM RTOs

Given the recently increased interest in VAM processing, a few innovations would have a significant positive impact on projects economics:

- Further development of the equipment's modularity facilitating relocation would help to lower the long-term capital costs; and,
- increase in energy recovery efficiency, allowing process fans to be powered by VAM-generated steam or a small-scale electricity generation infrastructure (such as organic Rankine cycle or Stirling engines), would lower the operating cost of moving the ventilation air from the évasé to RTO.
- If any of the ongoing catalytic development projects is successful, the introduction of an effective methane catalyst might increase the air volume processed per RTO and lower the cost of the process fan (pushing the ventilation air through the RTO units). Depending on the amount of catalyst applied, this might turn the RTO into a CTO.

Design aspects on flammability

In common with other gases defined as Volatile Organic Compounds (VOCs), methane in a typical thermal RTO generally oxidizes at a temperature ranging from 850 to 900 degrees C. In such conditions, a methane molecule breaks. Its hydrogen atoms form water vapor, while carbon combines with oxygen and forms CO_2. The process is exothermic and generates energy.

The recognized Minimum Auto Ignition Temperature (MAIT) of methane is 620 degrees C, however when considering VAM, the flammable gas is a natural gas that normally contains methane and other higher alkanes such as ethane, pentane, propane, and butane. The concentration of these other gases varies with the geology of the coal deposit but ranging from a mere trace at many mines (of limited consequence to oxidation or flammability), to having more than 10% of the total flammable gas part being ethane at other mines. Some mines have significant proportions of inert gases, such as CO_2, in their ventilation air. Thermal and catalytic oxidizers operation is unaffected by inert content.

When there is a significant amount of ethane within the gas mix, the Lower Flammability Limits (LFL) and MAIT are reduced. Le Chateliers can be used to calculate the effect of ethane on the gas mix LFL by using the actual gas analysis. Ethane has a MAIT of 472 degrees C and LFL 2.4% v/v.

Where ethane is present in the mix beyond 1% v/v of total flammable gas, it is recommended that a conservative approach to MAIT is taken and a process MAIT for the VAM gas mix or “methane” is considered to be 495 degrees C, equivalent to that of natural gas.

It is also recommended that the LFL of the flammable gas/methane is considered to be 4.3% v/v, for similar reasons of conservatism within a process safety design for a VAM abatement plant. The generally accepted mining industry standard LFL for methane is 5% v/v.

The actual oxidation temperature of a flammable gas mix from VAM will depend upon several factors including the gas analysis (as described above) and the temperature, residence time, and turbulence of the process design parameters of the thermal oxidizer being used. If we consider methane only, the Antonini Equation (1996) fixes the required combustion temperature for methane at a minimum of 844 degrees C to achieve 99.99% destruction with a residence time of 1.3 seconds in a two bed RTO unit. Where ethane is included, the required temperature drops to 715 degrees C. Where a single bed design is used, the effective oxidation temperature may need to be up to 1000 degrees C to compensate for the reduced oxidation residence time. In practical terms this means that the actual thermal oxidation temperature can range from 800 to 1000 degrees C, depending on the actual VAM gas analysis and configuration of RTO bed and media technology applied for oxidation.

ANNEX 3 - Examples of VAM installations

Global first three commercial VAM mitigation installations

The first successful on-site demonstrations of the RTO technology for VAM processing took place in the 1990s. However, the first three commercial VAM processing projects were commissioned in the first decade of the 21st Century:

***Figure A-III 1**: WestVAMP VAM Power Plant (Courtesy of MEGTEC-Dürr)*

- 2007: In Australia, at the WestCliff colliery of Illawarra Coal (belonging to BHP Billiton), supplier MEGTEC[10] (Sweden) commissioned a special power plant with 4 RTO units operating as furnaces using VAM with around 1% methane concentration, generating steam for a conventional 6 MWe steam turbine. The installation processed around 20% (250,000 m^3/h) of the full ventilation air volume of a major ventilation shaft (the customer wished the installation to be big enough so that scaling up to taking the full volume would not be an issue - but at the same time limiting the size and cost since the plant was the World's first commercial size installation of VAM RTO processing) and operated for 10 years. The project was halted because the underground (longwall) mining was relocated (in accordance with the plan), causing the VAM concentration to drop. See an image of the plant in **Figure A-III 1**.

***Figure A-III 2**: Single bed RTO installation at* GaoCheng mine *(Courtesy of MEGTEC-Dürr)*

[10] Since 2018, company Dürr has been the owner of MEGTEC.

- 2008: In China, supplier MEGTEC commissioned a single bed RTO installation processing a partial flow of around 60,000 m^3/h of ventilation air from the GaoCheng mine, generating hot water for local residential heating. The project was financed by the generation of Carbon Emission Reduction Credits (via the “Clean Development Mechanism”) under the rules of the Kyoto Protocol programme, attributing a value to the actual emission reductions achieved. The VAM Processing installation was operated for a few years, after which it was stopped due to the lower-than-expected VAM concentration in the ventilation shaft. See an image of the plant in **Figure A-III 2**.

Figure A-III 3*: Twin bed RTO at JWR (Courtesy of Biothermica)*

- 2009: In the USA, supplier Biothermica (Canada) commissioned a single unit RTO installation processing around 50,000 m^3/h of ventilation air at Jim Walter Resources (JWR). The installation was operated for 4 years and was halted due to a decrease in VAM concentration that led the mine to closure of the ventilation shaft in question. See an image of the plant in **Figure A-III 3**.

Figure A-III 4*: 3 Twin bed RTOs at the Marshall County Mine (Courtesy of Dürr)*

Other examples of successful VAM processing installations

- 2012: At the McElroy mine in the USA, supplier Dürr (USA, Germany) commissioned three sets of RTOs, with a total ventilation air processing capacity of 250,000 m^3/h. After more than 10 years of operation the VAM processing plant was shut down in 2023 due to low methane content. The plant is being prepared for relocation. This project highlights one of the benefits of RTO installations, i.e. the possibility of transferring the equipment to a new shaft when methane concentrations decrease below the technical or economic feasibility limits. See an image of the plant in **Figure A-III 4**.

Figure A-III 5*: 10 Twin bed RTOs at the GaoHe mine (Courtesy of Dürr)*

- 2014: At the GaoHe mine in China, supplier Dürr (USA, Germany, China) commissioned a VAM Processing installation with ten RTO units and the total ventilation air processing capacity of 1,020,000 m^3/h. The inlet concentration to the processing plant is being kept at approx. 1.1% methane by the addition of drainage gas. Hot gas ducting is connected to a boiler that feeds a 30 MWe steam turbine. After 10 years, the plant is still in operation. See an image of the plant in **Figure A-III 5** (ventilation air coming in from the left, feeding the RTOs, and exiting through the exhaust chimney on the right).

Figure A-III 6*: Six Twin bed RTOs at a Shanxi mine (Courtesy of Anguil Environmental)*

- 2016: At a Shanxi mine in China, supplier Anguil Environmental (USA) commissioned an installation of 6 RTO units with ventilation air processing capacity of 540 thousand m^3/h, and the installed electricity generation capacity of 15 MWe. After 8 years, the plant is still in operation. See an image of the plant in **Figure A-III 6**.

Figure A-III 7*: Large Twin bed RTO at Buchanan mine (Courtesy of Biothermica)*

- 2022: In the USA, supplier Biothermica commissioned at the Buchanan Coronado mine a VAM RTO installation with ventilation air processing capacity of 260 thousand m^3/h. See an image of the plant in **Figure A-III 7**. Another installation, with a capacity of 320 thousand m^3/h, was commissioned in 2024.

Figure A-III 8*: Two Rotary RTOs at the YuangXiang coal mine (Courtesy of Eisenmann Environmental Technology)*

- 2023: In China, RTO supplier Eisenmann Environmental Technology commissioned at the YuangXiang coal mine 2 sets of RTOs mitigating 240,000 m^3/h of methane in concentration of 1.2%, where 0.16% comes from VAM and the rest is supplied by drainage gas methane. Blending is done in a mixing box. Eisenmann's customer provided a steam boiler and turbines with the installed capacity of 5.5 MWe. See an image of the plant in **Figure A-III 8**.

Domestic Chinese VAM RTO plants

In China, there are also 3 operating VAM mitigation plants provided by the domestic suppliers. According to information provided by China Coal Information Institute (CCII):

***Figure A-III 9**: Ten RTO units at the Dafosi mine (Courtesy of CCII)*

- 2012: At the Dafosi coal mine in the Shaanxi Province, supplier ShengDong Group commissioned an installation consisting of 10 RTO units, with a total annual ventilation air processing capacity of over 30 million m^3 and the total electricity generating capacity of 30 GWh per year. Information about VAM and total methane concentrations are unknown. See an image of the installation in **Figure A-III 9**.

***Figure A-III 10**: VAM RTO of Yiyang Clean Energy of Zhejiang Province (Courtesy of CCII)*

- 2018: At a coal mine in the Anhui Province (Dingji coal mine of Huaihu Coal and Power Co. Ltd.), supplier Zhejiang Yiyang Energy Technology Co Ltd. commissioned an installation with 2 RTO units, with a total annual processing capacity of 30 million m^3. The concentration of methane ranges from 1 to 1.2% (a mixture of VAM and drainage gas), and the annual power generation capacity amounts to 28 GWh. See an image of the installation in **Figure A-III 10**.

Figure A-III 11*: VAM project in Yuwu coal mine (Courtesy of CCII)*

- 2020: At the Yuwu coal mine in the Shanxi Province, Supplier Shanxi Aerospace Guotai Clean Energy Co Ltd commissioned an installation with 1 RTO unit with the annual methane processing capacity of 16 million m^3. The concentration of methane ranges from 1 to 1.2% (a mixture of VAM and drainage gas), and the annual power generation capacity amounts to 30 GWh. See an image of the installation in **Figure A-III 11**.

Conclusions on global experience of RTO VAM mitigation

With decades of successful operation, VAM processing performed by RTO suppliers with the relevant experience from other industrial applications is well proven. Multiple projects in different countries have demonstrated the viability of VAM treatment as a large-scale, effective mitigation strategy. In addition, where suitable, a VAM plant can provide an additional benefit of generating energy.

For successful mitigation, it is important that the mining company and the project developer determine a sufficient certainty level and a variation in concentration of methane in the ventilation shaft considered for VAM processing. Such an assessment should also evaluate whether drainage gas could be safely injected into the ventilation air flow to increase the quantities of methane that is to be processed and mitigated, and if so, the available volumes of such gas.

Experienced RTO providers typically expect around 98% cleaning efficiency and 96% availability (i.e., 4% downtime is reserved for service).

ANNEX 4 - Global Warming, CO_2 and methane

The atmosphere of the Earth consists of three main gases: Nitrogen (78%), Oxygen (21%), and Argon (0.9%). The remaining 0.1% is a cocktail of many gases, some of which are capable of partially retaining the heating energy (infrared) radiation of the sun (these are the so-called Greenhouse Gases - GHGs) (see **Figure A-IV 1** and **Figure A-IV 2**). Thanks to that, the average temperature on Earth is +15°C. Without GHGs, the average temperature would have been -15°C, and the Earth would have been a frozen planet.

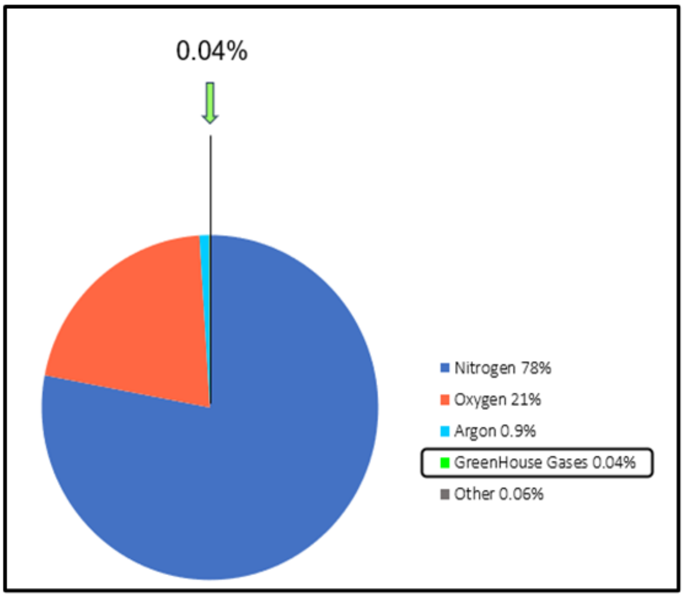

Figure A-IV 1*: The proportions of gases in the atmosphere*

The most important GHG is CO_2, followed by methane. While the share of the former in the atmosphere is approx. 0.04%, in the case of the latter it is only 0.0002% (in **Figure A-IV 1**, both are included in the portion of 0.04% labeled as GHGs)

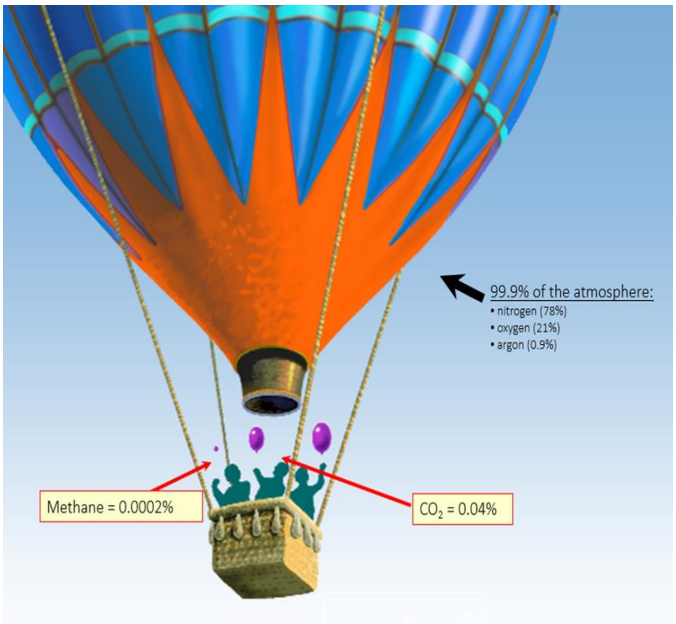

Figure A-IV 2*: Proportions of the atmospheric gases as volumes of balloons*

Due to industrialization, fossil deposits of coal, oil, and natural gas have been retrieved from underground and used as fuels for generating energy. These carbon deposits were taken out of the natural cycle of carbon some 300 million years ago. As they have been ever more intensively reintroduced back into the cycle of carbon since the industrial revolution, the CO_2 started to overflow the natural cycle and have been accumulating in the atmosphere, adding to the greenhouse effect, which causes the average temperature of Earth to rise above the previously established +15°C and thus also a climate change.

Like CO_2, emissions of methane have also increased since the start of industrialization.

CO_2 and methane

The biggest impact on global warming comes from the growing atmospheric content of CO_2, which has increased by around 50% since the 1880s. CO_2 is the end product of most oxidation processes, not subject to any further evolution or decay. As a result, an excess of CO_2 that is not absorbed by nature remains in the atmosphere for thousands of years.

The second biggest impact on global warming comes from the increasing atmospheric content of methane, which has doubled since the 1880s. Unlike CO_2, methane has a limited lifetime in the atmosphere. After around 12 years it oxidizes, forming CO_2 and water.

Figure A-IV 3 illustrates comparatively a long-term global warming effect of, on the one hand, CO_2 emissions produced over a single year by a fossil fuel-based power plant, and on the other hand methane emissions released over the same period of time from a coal mine ventilation shaft. **Figure A-IV 4**, in turn, illustrates the same comparison, but instead of focusing on emissions' volumes produced only over a single year, it shows the long-term environmental impact that the two gases have if they are generated continuously for a long period of time. The graphs in both figures assume steady emission levels of both CO_2 and of methane (CH_4).

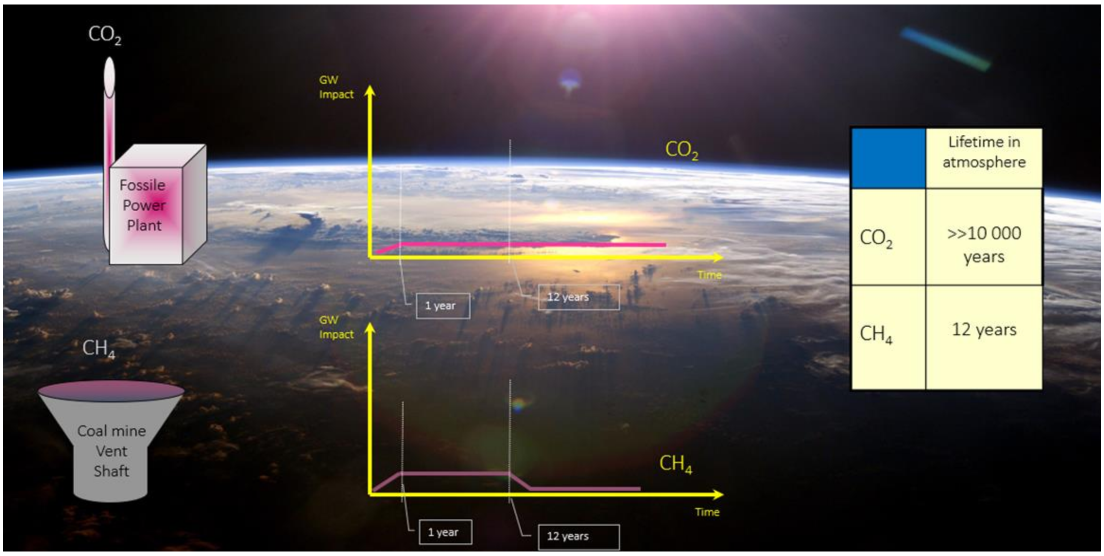

***Figure A-IV 3**: Comparison of a long-term environmental impact of one year of CO_2 and methane emission*

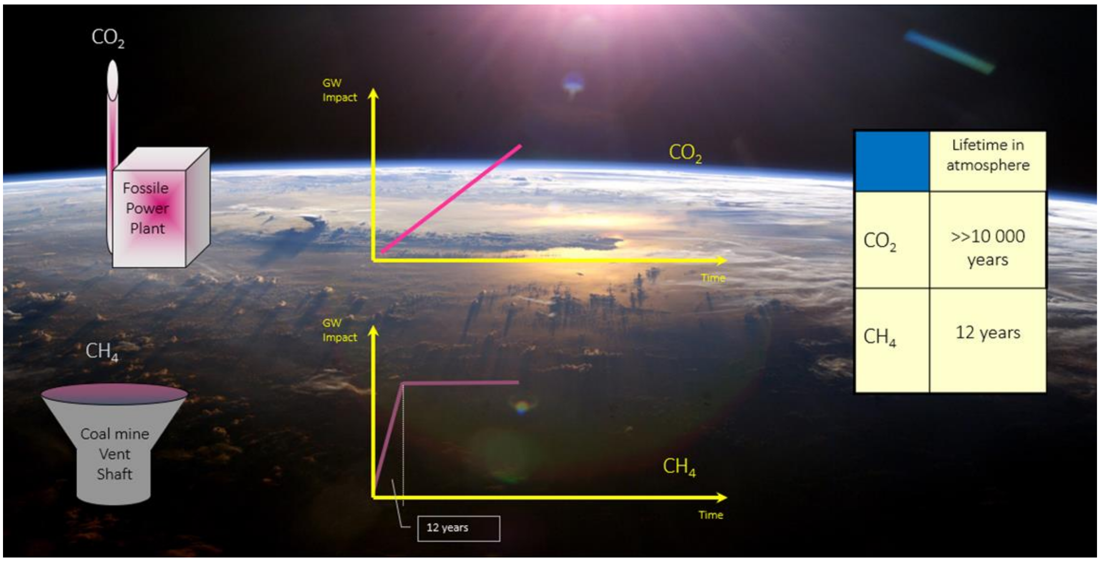

***Figure A-IV 4**: Comparison of a long-term environmental impact of CO_2 and methane emissions produced continuously and at a steady basis over a long period of time*

Due to the limited lifetime in the atmosphere, a major reduction of large emissions of methane will have an immediate positive impact on the environment, instantaneously reducing methane content in the atmosphere, and thus also its contribution to global warming (see **Figure A-IV 5**).

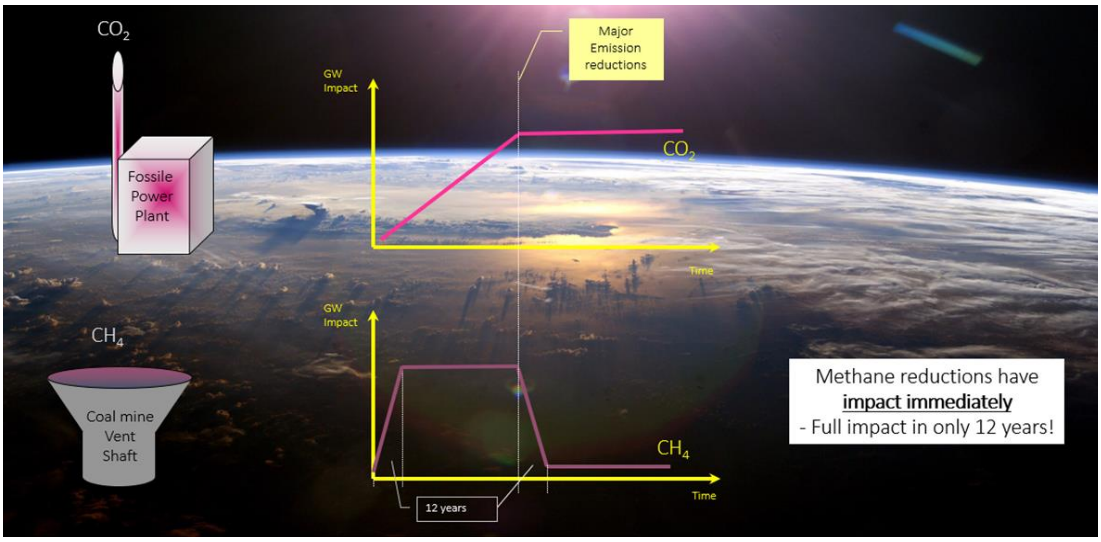

***Figure A-IV 5**: Comparison of a long-term environmental impact of major emission reductions of CO_2 and methane*

The Global Warming Potential (GWP) of methane

While a methane molecule can retain in the atmosphere much more heating energy than a molecule of CO_2, after 12 years when the former (methane) oxidizes into CO_2, the impact of both naturally became identical. Customarily, the impact on global warming of all GHGs is presented in the form of its ratio to the effect caused by CO_2 over a period of 100-years. In such comparison, methane has a GWP of 30[11]. However, as it was already discussed, all that impact comes from its large capacity to retain heat, which lasts only for 12 years, before its molecule oxidizes (see **Figure A-IV 6**). As a result,

[11] IPCC has been periodically updating its assessments of GWP of various GHGs. The latest version, the AR6, was published in 2021. Previously GWP of methane was indicated to be 25 rather than 30, as it is currently.

in the case of methane, adopting a 100-year-long perspective is somehow misleading, diminishing its true potency that it exhibits during its short lifetime.

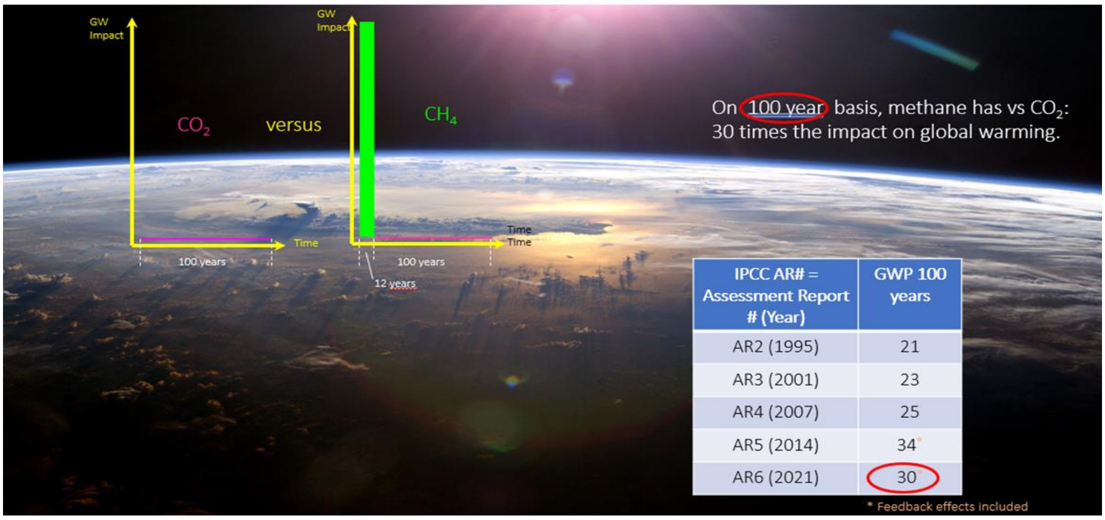

***Figure A-IV 6**: Comparison of GWP of CO_2 and methane over a period of 100-years*

With increasing awareness of the severity of the climate change situation, there is an increasing concern about the short-term effects of GHG emissions. Adopting a 20-year long perspective, methane GWP impact measured against CO_2 grows to 82 (see **Figure A-IV 7**).

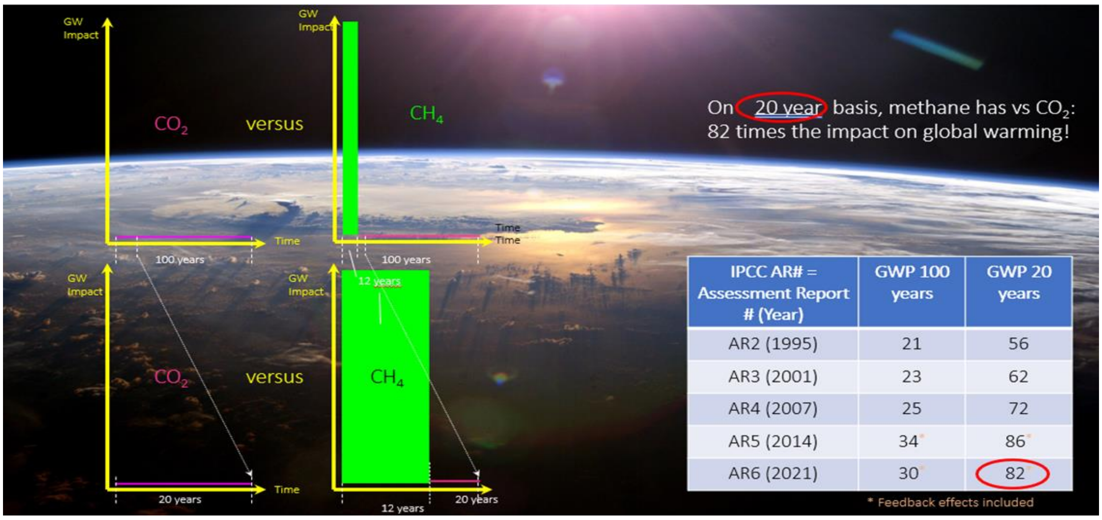

***Figure A-IV 7**: Comparison of GWP of CO_2 and CH_4 over a period of 20-years*

It is the factor of 30 that is, and most likely will continue to be used as a basis for calculating the results of methane emission reduction efforts and initiatives, whereas the factor of 82 should be used as a basis for comparing and evaluating their actual positive effects for the near future over the next 20 years.

On an overall level, efforts to reduce emissions of CO_2 need to be combined with efforts to reduce large emissions of methane, such as VAM mitigation.

ANNEX 5 - The parallel history of Carbon Credits trading and VAM processing

The 1992 Climate Conference in Rio de Janeiro, Brazil, constituted the first call to start thinking about reducing major emissions of GHG. The participants decided to establish the UN Framework Convention on Climate Change (UNFCCC).

The first ever successful on-site VAM demonstration took place at the Thoresby Mine of British Coal in 1994. It operated over several months during which the technical possibility of efficiently cleaning out methane from ventilation air by RTO technology was proven.

Being in search of a technology able to handle very large volumes of ventilation air characterized by an extremely low content of methane, BHP in Australia reached out to the Swedish company that was behind the VAM processing demonstration in the UK. This led to another demonstration, lasting for over 12 months, where a small size industrial RTO was processing 6,000 m^3 of a side stream of the ventilation air per hour, showing not only that it had no problems with handling the swings in methane concentration (resulting from the underground operations) but also that boiler tubes embedded in the equipment could use the energy released during VAM oxidation to efficiently boil water to steam.

BHP's VAM-to-steam project was located at the Appin site, near an installation of Caterpillar gas engines operating on drainage gas, where as a trial, a small side stream of ventilation air was used as combustion air (in other words, VAM was used as a supplementary fuel).

In 1997, the same year in which the 12 months Appin VAM RTO trial was set up, another milestone climate conference was held, in Kyoto, Japan. It resulted in the adoption of the Kyoto Protocol, a global agreement to reduce GHG emissions to 5% below the 1990 levels, and to introduce in support of this effort a trading mechanism called carbon credits (see **Chapter 6**).

Trading floors for carbon credits (officially issued rights to emit certain volumes of CO_2) started to establish and expand. The official launch of Kyoto-related carbon credits took place in 2005, with the regulated period of 2008-2012. The world's largest trading scheme of the time was the EU Emissions Trading Scheme (ETS).

In 2004, when Australian BHP had merged with the South African Billiton, and the Swedish emission control company was acquired by the US-based MEGTEC, the two companies signed an agreement to develop the world's first commercial scale VAM processing installation. The project was designed to process 250,000 m^3 of ventilation air per hour and became known as WestVAMP (the West Cliff Ventilation Air Methane Plant), a hybrid project combining the traditional emission control technology of RTO and the steam cycle of a traditional power plant. MEGTEC integrated the two technologies by introducing the RTO into the steam cycle as a furnace capable of operating on the basis of the extremely diluted methane concentration typical for VAM.

BHP Billiton allowed MEGTEC to present the technology and the WestVAMP project as soon as the agreement had been signed (in April 2004). The word was spread at mine gas conferences in Australia, US, Europe, and China. When WestVAMP was successfully commissioned in April 2007, it attracted major international interest. It also won MEGTEC several international awards, such as e.g., the US EPA's 2008 Climate Protection Award.

In 2007, MEGTEC started yet another large-scale RTO demonstration at an abandoned mine site of CONSOL Energy in the US. The applied installation processed 60,000 m^3 of fresh air, into which high concentration methane from the abandoned Windsor Mine was injected to simulate VAM of different concentrations.

In 2009, the first VAM processing plant in China was commissioned, also supplied by MEGTEC. It processed 60,000 m^3 of air per hour, using the retrieved energy to generate hot water for the heating of nearby buildings.

Considering such promising results, several of MEGTEC's industrial RTO competitors started to show interest in the VAM application. So did lso several companies from other industries, seeing a large business potential in VAM treatment.

At the same time, the trading volumes and the price level of carbon credits continued to steadily grow (see **Chapter 6**) until the UN Climate Change Conference in Copenhagen in November 2009, which was intended to extend the validity of the Kyoto Protocol beyond 2012. However, as the conference failed to do so, the VAM market rapidly stagnated and almost disappeared.

In 2011, MEGTEC commissioned another VAM plant in China, processing 50% more ventilation air volume than the WestVAMP and generating hot water for the local use.

In the same year, Canadian RTO supplier BioThermica, commissioned a large-scale (60,000 m^3 per hour) VAM abatement plant at Jim Walter Resources in the US.

In 2012, MEGTEC's major industrial emission control competitor Dürr commissioned its first large scale (250,000 m^3 per hour) VAM abatement plant at the McElroy mine in the US.

In 2016, US RTO supplier Anguil Environmental commissioned its first VAM plant in China.

Two years later, in 2018, German RTO supplier Eisenmann Environmental commissioned its first coal mine methane RTO plant also in China.

Domestic Chinese suppliers entered the field of RTO VAM processing as well. ShenDong as early as 2012, Zhejiang Yiyang Energy in 2018, and Shanxi Aerospace Guotai Clean Energy in 2020.

The way forward

With the signing of the Global Methane Pledge (2021), 159 countries (as of November 2024) from around the world committed to reduce their joint methane emissions by 30% by 2030.

Given the increasing urgency of taking efficient actions against the global warming and climate change, and the very slow rate of global conversion from fossil fuels to sustainable types of energy, it is likely that the focus on reducing major emissions of methane will over the next years increase on a global scale.

Large, single source methane emissions should be of interest, as they offer great and quickly achievable mitigation results. One such opportunity with a significant positive climate impact is VAM mitigation.

Securing financing for VAM emission reductions at the level of approx. USD $20 per tCO_2e over the first 4-5 years of plant operation should be sufficient and key to attracting the urgently needed investments in that field.

There is an increasing number of carbon trading schemes and many of them are starting to include methane emission reductions. Efforts are also being made to coordinate their activities. Based on the values at which trading is taking place, as soon as VAM mitigation projects are included into those schemes, they would become very attractive, as their mitigation cost efficiency at around USD $20 per avoided tCO_2e is substantially better than that offered by many of the alternative options.

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