Expert Dialogue on Ventilation Air Methane (VAM)
Melbourne, Australia
25 October 2018
Meeting Report

Sponsor

Commonwealth Scientific & Industrial Research Organization (CSIRO) of Australia

Supporters

Global Methane Initiative
U.S. Environmental Protection Agency

Agenda

The agenda is included as Appendix A.

Participants

The list of participants is included as Appendix B.

Background and objectives of the Expert Dialogue

Methane is the second largest source of anthropogenic greenhouse gases (GHGs), accounting for 16 percent of global GHG emissions.[1] Reduction of these emissions has become a policy priority in recent years due to methane's high global warming potential (GWP) which is 28 to 34 times greater than that of CO_2.[2] In addition to the climate benefits of lower emissions, mitigation of methane emissions also results in important economic, safety, and environmental co-benefits.

Coal mines are a leading source of methane, accounting for 9% of global methane emissions, making the mining industry the fourth largest anthropogenic source. The Global Methane Initiative (GMI) estimates that current global coal mine methane (CMM) emissions total 800 million tonnes of CO_2 equivalent ($MTCO_2e$), with the largest share of emissions coming from ventilation shafts at underground coal

[1] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
[2] IPCC, 2014.

mines.[3] Although access to worldwide CMM data is limited, it is generally assumed that ventilation air methane (VAM) emissions make up about 70 percent of all CMM emissions. Thus, projects and/or practices reducing VAM emissions will have to be deployed on a large scale to achieve significant GHG emission reductions from the coal production sector. However, VAM technology and project development have lagged implementation of more conventional CMM projects (e.g., gas drainage to power projects) due to a range of policy, technical and economic barriers.

CSIRO hosted the Expert Dialogue on Ventilation Air Methane (VAM), under the auspices of international collaboration with the GMI on 25 October 2018 in Melbourne, Australia. The objective of the Dialogue was to bring international experts together in an open, collaborative environment to more thoroughly and candidly explore the technical, market and policy barriers that are inhibiting VAM project implementation. This was the second of two dialogues. The first discussion was held in Geneva, Switzerland on 24 September 2018 during the GMI Coal Subcommittee Meeting.

The other objectives were to develop a discrete list of achievable tasks or actions that could support increased VAM project development and to start a continuing dialogue among GMI stakeholders and other interested parties. The meeting was held under Chatham House Rules to encourage an honest and open discussion.[4] T*his report, therefore, does not attribute any view, position, statement or comment to a particular individual or organization whilst providing a summary of the discussions and outcomes of the Dialogue.* However, the authors of the three opening "scene-setting" presentations have agreed to distribute their presentations to the participants at the meeting and to a limited number of individuals who were invited but were unable to attend.

CSIRO and GMI have asked persons receiving the presentations to not distribute them to other parties without the written consent of the authors.

Prior to the meeting, participants were sent 6 questions prior to the meeting, and these questions served as the basis for the discussion:

1. What do you consider the key drivers to increased VAM project development in the next 5 years?
2. What is your opinion of the current state of technology development and innovation to support project development?
3. Is VAM a bonafide energy resource for waste heat recovery projects, or is abatement the only realistic option to roll out on a large scale?
4. Are potential opportunities for VAM emission reductions being messaged effectively to carbon market stakeholders?
5. Do we have accurate worldwide VAM emissions estimates? Where are the gaps?
6. What specific GMI roles or products do you believe would further VAM mitigation?

---

[3] U.S. Environmental Protection Agency. (2012). Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030. U.S. Environmental Protection Agency, Office of Air & Radiation. EPA 430-R-12-006, December 2012

[4] Chatham House Rule - "When a meeting, or part thereof, is held under the Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed." https://www.chathamhouse.org/chatham-house-rule

The meeting opened with a brief welcome and introductory remarks from representatives of the sponsoring organizations: Hua Guo, Ph.D., CSIRO and Felicia Ruiz, GMI Coal Subcommittee Co-Chair and Team Leader, U.S. Environmental Protection Agency (EPA) Coalbed Methane Outreach Program.

Following the introductory remarks, brief "scene-setting" presentations were delivered to provide a foundation for the ensuing discussions:

- *Global VAM Update* – Richard Mattus, RM Consulting Ltd (Sweden)
- *Status of VAM Abatement Science & Technology* – Dr. Shi Su, CSIRO (Australia)
- *Ventilation Air Methane: Australian Industry Perspective* – Jim Craigen, Coal21, (Australia)

The facilitator, Sarah Cleary, Ph.D., CSIRO, then opened the meeting for discussion. The following summary attempts to present the major points raised during the discussion.

Major Themes

- VAM accounts for approximately 70% of global CMM emissions and an effective strategy to significantly reduce methane emissions in the coal sector will require large-scale deployment of VAM abatement projects.
- The magnitude of emissions combined with the limited number of facilities and ventilation shafts makes VAM potentially attractive as a GHG mitigation target compared to many other GHG sources.
- VAM can be used as a primary or ancillary source of fuel but use as a primary fuel offers the greatest mitigation potential.
- Regenerative Thermal Oxidation (RTO) technology has achieved commercial scale and continues to be used in multi-year commercial operations.
- Other technologies including lean-burn catalytic turbines, lean burn thermal turbines, and concentrators are in research, development & demonstration (R,D,&D) mode with field tests of lean burn catalytic oxidation technology achieve sustained operation at 0.80% CH_4.
- Only 3 VAM projects are currently operating worldwide, with two projects reportedly in development. All current and previously operating commercial VAM projects have relied on RTO technology.
- Deployment of VAM projects face many technical, safety, policy, and market barriers.
- Technical barriers include: low CH_4 concentrations, the large footprint of VAM projects, potential impact on the mine ventilation system, fluctuations in methane concentrations, dust tolerance, and high-power consumption.
- The most significant safety concerns discussed were ignition risk potential disruption to the mine ventilation system. In Australia there was acknowledgement that designs include important safety features such as flame arrestors, etc. but the limited number of demonstration and commercial projects to date does not serve as a fully adequate demonstration of safe design and operation. To encourage wide-scale acceptance, some believe that the industry should develop and implement a fail-safe option ready for deployment at scale.

- Following initial concerns, mine safety regulators and mining companies in the U.S. and China have accepted VAM oxidation as a safe CH_4 emission abatement option with the appropriate design and safety features in place.
- There are very few incentives to implement VAM projects. Incentives can take the form of a "carrot" such as sufficient carbon or power prices or a "stick" such as regulatory penalties.
- Carbon prices of US$ 10-12/t CO_2e are considered breakeven costs for higher concentration shafts; however, only the U.S. currently has a carbon market with prices that can sustain a VAM project. Chinese projects rely on high electricity prices and government incentives to pay for VAM-to-Power projects.
- With respect to "sticks," some countries tax emissions or have penalties for excessive emissions; however, the requirements are reportedly rarely enforced or incur minimal penalties.
- Newer or lower producing mines may be disproportionately impacted by carbon-based incentives or penalties because they are less likely to employ gas drainage systems or will employ less extensive drainage systems. Most or all of emissions from these mines are VAM emissions.
- VAM oxidation projects are very expensive. VAM manufacturers have little interest in further R&D to improve designs and reduce costs without the existence of confirmed markets. Most likely, improvements will made through continued R&D by organizations such as CSIRO or by manufacturers working on commercial projects.
- Where possible, it may be more effective to invest in increased gas drainage, even when not required for safety.
- VAM is a major source of GHG emissions, especially in major coal mining countries, yet VAM abatement has limited visibility. The coal industry and other stakeholders have not succeeded in developing and conveying a clear vision to advance VAM use even though the potential advantages of VAM emission reductions can underpin a very strong message.

Outcomes and recommendations

The following are potential outcomes and recommendations for further GMI Coal Subcommittee / stakeholder action:

- To address safety concerns:
  - Continue R,D&D to further refine design and operation of VAM use technologies. Reduction of oxidation temperatures and elimination of ignition and flame propagation risks are critical, although it will be nearly impossible to develop a technological solution that will be proven to be completely risk-free.
  - Prepare case studies of commercial projects with detailed design and operational information. However, it may be difficult to obtain design and operating data, some of which will be confidential.
  - Study tours to China and the U.S. were also proposed. The study tours would visit operating sites and provide the opportunity to meet with the mine safety authorities and the mining industry. There was interest, and some participants believed that such tours could have value. However, some Australia representatives responded that such

tours would be expensive, would not substitute for ongoing work in Australia, and would not necessarily result in any action.
    - Installation of test-scale or commercial-scale RTOs at an experimental mine used for mine safety research and then ignition of the VAM to assess the behavior of flame propagation and to design and test safe equipment, practices and operations. While there was interest in this idea, there was also acknowledgement that this type of R&D project would be very expensive. Further, the experimental mines may not be analogous to mine design and operations in all countries.
    - In cooperation with GMI, Steven Wan of Fortman (Beijing) Clean Energy Ltd. and a participant in the VAM Dialogue, has offered to set up a tour of the China VAM facilities in Spring 2019 and to discuss VAM with government officials in China. Fortman is the developer of the Gaohe and Yangquan VAM projects.
- To address policy/legal barriers:
    - Prepare a policy paper analyzing the impact of the California Cap-and-Trade program on the development of VAM projects in the U.S. surveying the mining industry, project developers and buyers of carbon credits. The purpose would be to identify those aspects of the Cap-and-Trade that are successful in encouraging implementation of VAM projects while also identifying disincentives.
    - Prepare a comparative policy analysis providing an update and review of regulatory and market drivers across major mining countries with an assessment of what has worked and what hasn't worked.
- To address market/economic barriers:
    - Prepare a global VAM resource assessment summarizing mine-specific opportunities.
    - New or improved VAM abatement technologies with simple processes, lower energy consumption, and excellent tolerance with dust contained in ventilation air to substantially reduce capital, operational and maintenance cost
    - A marginal cost study was proposed based on input from the first Dialogue in September. The study would consider the marginal cost of implementing VAM projects versus the cost of increased gas drainage. There was some interest in this proposed concept, but there were also some concerns that were raised.
        - Any marginal cost study would most likely be site-specific. The mining operations and mining conditions at each mine are unique. The marginal cost of gas drainage and VAM project implementation at the study mine may not be reflective of the ability to implement these projects, the associated costs of doing so or the ensuing results that would be achieved at operating mines.
        - The costs of possible delays in mine development and longwall production due to more extensive gas drainage or longer drainage times would have to be considered in the economic analysis.
        - In some cases, even increasing gas drainage will not change the volume of methane emitted from mine ventilation shafts. The reduction in in-situ gas content (pre-drainage) or gas emissions into the mine (post-drainage) will result in increased advance rates and increased coal production with the end-result being VAM emissions remain steady and total gas liberated from the mine (VAM + drainage) increases.

- To address concerns about messaging:
    - An effective briefing paper and outreach campaign could be developed followed by direct outreach to the investment community and policymakers.
    - A China-based case study could be developed evaluating the social impacts, economic impacts and environmental impacts of VAM projects.

Report Appendices

Appendix A - Agenda for the Expert Dialogue on VAM

Appendix B – List of Participants

Detailed Summary of the Dialogue

VAM Resource

- VAM is the largest source of methane emissions from coal mines. Estimates are that VAM emissions are 70 percent of total global coal mine methane emissions.
    - Emissions vary from country to country
    - Australia: VAM = 66% of underground CMM emissions[5]
    - China: VAM = 83% of total CMM emissions[6]
    - US: VAM = 52% of total CMM emissions and 64 percent of underground CMM emissions.[7]
- Shaft flows can range from 150 – 600 m^3/s.
- To understand the magnitude of VAM emissions and the potential for GHG abatement:
    - A shaft emitting 222 m^3/s (800,000 m^3/h) at 1 percent CH_4 will emit ~1 million tCO2e in a year.
    - The largest commercial VAM projects are on par with early stage commercial Carbon Capture Utilization and Storage (CCUS) projects and could serve as an important interim solution to further reducing the carbon footprint of the coal industry as CCUS moves toward wider commercial application.
        - The Gaohe VAM Project in China operating at full capacity could reduce emissions by 1.3 $MTCO_2e$ annually and the Marshall County VAM project in the U.S. is averaging emission reductions of 270,000 tCO_2e.

[5] Shi, Su (2018). Status of VAM Abatement Science & Technology. 25 October 2018. Melbourne, Australia.
[6] Reported Steven Wan, Fortman (Beijing) Clean Energy Technology Ltd. October 2018
[7] EPA (2018). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. Washington, D.C. USA. April 2018.

Status of commercial VAM project deployment

- VAM can be used as a primary or ancillary fuel source.
  - Primary fuel source: RTO, RCO, steam turbines, catalytic lean turbines, thermal lean turbines, methane concentrators to enrich the VAM concentration, and photocatalytic oxidation. May require supplementary fuel when recovering energy or generating power.
  - Supplemental or ancillary fuel: VAM as combustion air in combustion engines, coal-fired boilers or turbines. Requires siting of the power plant near a VAM source.
- Thus far all commercial projects have employed Regenerative Thermal Oxidation (RTO) (a.k.a., Thermal Flow Reversal Reactor (TFRR)) or used VAM as combustion air in internal combustion engines. A commercial Regenerative Catalytic Oxidizer (RCO) (a.k.a, Catalytic Flow Reversal Reactor (CFRR)) was constructed and commissioned in China but never was never operated commercially.
- Current: There are three operating commercial VAM projects worldwide, although all three are comparatively large projects:
  - Marshall County mine VAM project (USA): 75 m^3/s capacity using 3 RTO's (destruction only). From 2012 through 2017, the project produced 1.15 $MtCO^2e$ in emissions reductions and has averaged 270,000 tCO^2e per year the past three years.
  - Gaohe mine VAM project (China): 300 m^3/s capacity using 12 RTO's with 30 MW steam turbine power plant.
  - Yangquan Sangzhang VAM project (China): 150 m^3/s capacity using 6 RTO's with 15 MW steam turbine power plant.
- Past: From 2007 through 2016, additional projects are known to have operated but are now closed: China (3), Australia (2), and the U.S. (1). One of the Australia projects used VAM as combustion air. All other projects consisted of RTOs including one China project that also included an RCO.
- Future: 2 projects are reported to be under development in China and several may be under contract or at the early stage of development in the U.S. based on discussions with project developers and mine operators.

Status of VAM research and development

- For more information refer to presentation *Status of VAM Abatement Science & Technology* by Dr. Su Shi, CSIRO.
- RTO's
  - A technology originally designed for VOC abatement, RTO's have been continuously adapted to the VAM environment as projects are commercialized.
  - A significant challenge thus far has been management of excess heat generated by higher concentration shafts or VAM that has been enriched with drained CMM.
- RCO's, catalytic lean and thermal turbines and VAM enrichment
  - RD&D has advanced development of these technologies toward commercialization.
  - RCO's: Tested and demonstrated at lab scale and at commercial scale but have not operated continuously at a mine site at commercial scale.

    - Catalytic lean turbine: 25 kW prototype unit trialed at a mine site with a minimum 0.8 percent CH_4.
    - Enrichment using carbon absorbents: Large scale unit trialed at a mine site.
- Advancements in the R,D&D of VAM abatement technology have slowed with the lack of financial incentives or penalties to drive VAM project development.

Technical barriers to VAM deployment

- Low CH_4 concentrations
- Fluctuations in CH_4 concentrations
- Energy consumption
- High oxidation temperatures
- Dust and moisture in the return air
- Size and complexity of VAM abatement operations
- Low CH_4 concentrations
    - VAM projects have succeeded where CH_4 concentrations are high, such as the U.S. where bleeder shafts can approach 1.5-2.0% CH_4, or where VAM has been enriched with drained CMM to achieve a consistently higher CH_4 concentration approaching 1.0%, such as at the two currently operating projects in China.
    - The lower technical limit for oxidation is currently ~0.15-0.20% CH_4, the average CH_4 concentration in many shafts falls below the lower limit. However, it may not be necessary to reach below this lower limit. In the U.S., the highest concentration shafts account for a large share of nationwide VAM emissions.
    - For use of VAM in other technologies such as lean fuel turbines, tests of CSIRO's VAMCAT have shown that the technology can operate at 0.80% CH_4. Manufacturers of other designs have reported operation at concentrations of 1.2-1.5% CH_4. These concentrations are achievable for a very limited number of shafts.
- Fluctuations in CH_4 flow
    - RTOs and RCOs can handle reasonable fluctuations in mine vent shaft CH_4 concentrations when designed as destruction-only projects. Use of RTOs/RCOs to generate power using steam turbines and other technologies such as lean-burn turbines require a consistent CH_4 flow.
    - RTOs/RCOs may not be able manage wide fluctuations very well, especially as the average CH_4 concentrations move to the lower or upper technical limits which result in shutdown of the units.
- Energy consumption
    - RTO projects require fans to pull ventilation air through ductwork into the oxidizer. The fan's power consumption represents a significant operational expense for a VAM project. Reduced pressure drop across the oxidation bed would require less fan power decreasing both the capital costs required for the fan motors and the variable operating costs to provide consistent pressure.
    - This is an especially challenging issue in countries where industrial power prices are high, for example in China where power prices can be ~US$0.09 – 0.11/kWh. One

example from a former commercial project in China suggested that power consumption for an oxidation project could account for 40% of life-cycle costs.
  - With very low power prices in the U.S. coal producing regions (~US$0.04/kWh), power consumption still accounts for a sizeable share of life-cycle costs it's share is considerably smaller.
  - The energy consumption issue has also been a policy concern in China where abatement-only projects can be challenged because they can draw large loads from the Grid when policymakers are looking to increase delivery of power to the grid.
- High oxidation temperatures
  - The high oxidation temperatures in RTOs have resulted in design problems for some test and commercial designs, in particular at shafts with high CH_4 concentrations. The elevated temperatures have resulted in damage to the units requiring additional and reinforced material, increasing costs. Some units now employ hot-side bypasses to release excess heat.
- Dust and moisture in the return air
  - Dust and moisture can cause problems for oxidizers and other technical options such as lean fuel turbines and internal combustion engines where VAM is used as combustion air. Filters can be used to removed dust although this adds costs and may increase pressure drop.
- Size and complexity of oxidation units
  - A major concern of the mining industry is the large size and complexity of VAM oxidation plants. Oxidizer equipment, ductwork, fans and control houses require significant space adjacent to a ventilation fan and integration with the mining operation and mine's ventilation system. However, a VAM oxidation project does not contribute to the mine's core business, so there is limited interest from mining companies in placing these large operations at a mine site unless there are other drivers such as regulatory requirements, penalties, revenues, or energy recovery.
  - In some cases, mines simply do not have the space to host a VAM oxidation project.
- *Recommendations to address technical barriers were cross-cutting with recommendations to address other barriers, notably safety, market and economic barriers.*

Perceived safety barriers to VAM development

- Discussion of safety concerns was a major point of discussion during the dialogue, and it was agreed by all that safety is the highest priority for any abatement option.
- The most significant safety concerns discussed were:
  - Ignition risk
  - Potential disruption to the mine ventilation system
- Ignition risks
  - Ignition risks were acknowledged as a significant risk that has been addressed at test prototypes and commercial projects with use of ducting, sensors, flame arrestors, explosion doors, and automated vents to draw fresh air into the ductwork when CH_4 concentrations are too high. However, as noted below, some still question whether these safety features are enough.

- Disruption to the mine ventilation systems
    - The primary concern with disruption to the ventilation system is back pressure on mine ventilation fans.
    - To avoid back pressure, VAM projects implemented to date have not connected directly to the evasé, instead relying on a separation between the fan mouth and ductwork taking a slip stream of the VAM to the oxidizer. By using blowers to produce vacuum in the ductwork, the VAM is drawn away from the vent fan to the oxidizer.
    - At this time no participant was aware of any mine safety regulator that would allow a direct connection to the evasé. While a direct connection would likely increase the efficiency of the VAM project, there was acknowledgement that separation has worked well thus far, although there has been R&D in Australia to assess the efficiency of separation versus direction connection.
    - Separation is also viewed as a practice to reduce ignition risks.
- In Australia, the safety issues are not settled.
    - Acknowledgement that designs include important safety features such as flame arrestors, etc. but the industry needs a fail-safe option ready for deployment at scale.
    - The small number of global projects implemented to date have not sufficiently demonstrated safe operation according to some industry participants.
    - The demonstration project at the West Cliff Colliery (WestVAMP) was raised as a commercial-scale project that demonstrated safe operation at an active mine through its project life. However, there were comments suggesting that WestVAMP was not a sufficient demonstration project with respect to safety even it was a successful technical demonstration. The comments noted that the West Cliff Colliery had a long return and the safety mechanisms were appropriate for that specific mine. It was noted that other mines have shorter returns.
    - The Australian industry doesn't expect to meet the VAM industry to meet its safety standards in the next five years.
- In contrast, mine safety regulators and mining companies in the U.S. and China have accepted VAM oxidation as a safe CH_4 emission abatement option with the appropriate design and safety features in place.
- U.S.
    - Significant effort was made to work closely with the regulator, Mine Safety & Health Administration (MSHA), to develop a safe technical approach that considers mine-specific conditions. In addition to considerable engagement between the USEPA and MSHA, from 2005-2009, USEPA and the U.S. Department of Energy co-funded a commercial-scale RTO demonstration project with CONSOL energy at a closed mine where varying CH_4 concentrations and air flows simulated operating conditions. The demonstration project provided valuable health and safety data for MSHA.
    - Concerning U.S. regulatory approval, there is no "approved" RTO/RCO design. VAM projects are approved on a case-specific basis. Addition of a VAM project requires modification of the mine ventilation plan which must requires an extensive regulatory review before approval by MSHA.

- The U.S. requires that oxidation equipment be 100 feet (31 meters) from the fan mouth and that ducting with the appropriate sensors, arrestors, and other features be used to transfer VAM to the RTO/RCO.
- Although it has approved two projects, the agency neither encourages or discourages VAM projects – it remains neutral since CMM emission abatement is voluntary in the U.S.
- It was also noted that neither U.S. project experienced safety problems during their operation. The largest project, the Marshall County Mine VAM project, has been operating since 2012 without an ignition incident. Both U.S. projects have operated at bleeder shafts and neither has enriched VAM with drained gas.

- China
    - China is now leading efforts to deploy VAM abatement projects with two large-scale VAM-to-Power projects in operation and third in development. Previously two large-scale and two smaller abatement-only projects operated in China.
    - In addition, CSIRO has also tested a lean-burn turbine at a mine in China.
    - Authorization for construction and operation of a VAM project in China requires approval of the State Administration for Worker Safety (SAWS) and review by the Chongqing Design Institute. Following initial concerns, the mine safety authorities and the mining industry have accepted the technical viability and the safety of VAM oxidation projects with appropriate safety features.
    - Like the U.S., ductwork takes a slipstream of the VAM to the RTOs. There is no direct connection to the evasé.
- *To address safety concerns, some ideas were put forward:*
    - *Continue R,D&D to further refine design and operation of VAM use technologies. Reduction of oxidation temperatures and elimination of ignition and flame propagation risks are critical, although it will be nearly impossible to develop a technological solution that will be proven to be completely risk-free.*
    - *Prepare case studies of commercial projects with detailed design and operational information. However, it may be difficult to obtain design and operating data, some of which will be confidential.*
    - *Study tours to China and the U.S. were also proposed. The study tours would visit operating sites and provide the opportunity to meet with the mine safety authorities and the mining industry. There was interest, and some participants believed that such tours could have value. However, some Australia representatives responded that such tours would be expensive, would not substitute for ongoing work in Australia, and would not necessarily result in any action.*
    - *Installation of test-scale or commercial-scale RTOs at an experimental mine used for mine safety research and then ignition of the VAM to assess the behavior of flame propagation and to design and test safe equipment, practices and operations. While there was interest in this idea, there was also acknowledgement that this type of R&D project would be very expensive. Further, the experimental mines may not be analogous to mine design and operations in all countries.*
    - *In cooperation with GMI, Steven Wan of Fortman (Beijing) Clean Energy Ltd. and a participant in the VAM Dialogue has offered to set up a tour of the China facilities in*

Spring 2019 and to discuss VAM with government officials in China. Fortman is the developer of the Gaohe and Yangquan VAM projects.

Legal/policy barriers to VAM deployment

- Without a “carrot” or a “stick, there is no incentive to operate a VAM project.
    - “Carrots”
        - Adequate and sustained carbon credit price
        - High electricity prices to support VAM-to-Power projects
        - Government subsidies
        - Tax abatement
        - Renewable energy credits, feed-in tariffs or other environmental attributes
    - “Sticks”
        - Regulatory cap with penalties sufficient to drive behavior
        - Pollution control requirement with penalties
        - Carbon tax
- Sticks
    - Although some countries tax emissions or have penalties for excessive emissions, the requirements are reportedly rarely enforced or incur minimal penalties.
    - There are no known countries that require pollution abatement control equipment to be placed at mine ventilation shafts.
    - With the effective end of the Kyoto markets, there is no global compliance system for carbon credits. Voluntary carbon markets are active, but the prices are very low and are not sufficient for a VAM project. Current voluntary market prices are reported by project developers to range US$0.50 – 5.00/t$CO_2$e, but these prices could not be confirmed by participants in the meeting. Even if the higher prices exist, and there was some skepticism that they do, prices in voluntary markets remain too low to finance VAM projects. In the discussion, it was noted that even in the U.S. where some bleeder shafts operate at 1.5% CH_4, an accepted breakeven carbon price for a VAM RTO project is US$10-12/t$CO_2$e. In Australia, the breakeven price is assumed to be around AU$20/t$CO_2$e. Some believed that these breakeven costs are high; however, it was clarified that these costs are “all-in” costs including all capital, operating, and development costs and are based on actual projects that have been implemented.
    - One concern raised in the discussion was the potential for penalties or taxes that would result in perverse incentives whereby newer or lower producing mines would be disproportionately impacted since they are less likely to employ gas drainage systems or employ less extensive drainage systems. Most or all emissions are VAM emissions.
- Australia
    - There is currently no incentive for industry-wide deployment and no accepted industry-wide emissions target.
    - The coal industry in Australia expects some requirement or target to be imposed at a future date, but there is uncertainty about what form it will take and when it will be applied.
- China

   - With respect to China, VAM projects cannot participate in the provisional Chinese carbon markets. The two VAM projects currently operating in China reportedly do not require carbon credits, but instead rely on high industrial prices for sale of electricity or to offset electricity purchases from the grid.
- U.S.
      - Today the U.S. is the only country with a carbon price sufficient to encourage VAM projects. The functioning carbon market for CMM and VAM projects in the U.S. is the California Cap-and-Trade program. The Cap-and-Trade program allows VAM emission offset projects from anywhere in the U.S. to participate in the program, even if from outside California. The current price of carbon is US$14.00-15.00/t$CO_2$e which makes the highest concentration shafts economic. A number of VAM projects are reported to be under contract for development, but confirmation of these projects has not been made public.
      - The Cap-and-Trade program was originally set to expire in 2020, but in 2017 it was extended to 2030. However, after 2020 the number of offsets allowed into the market is halved and then only 50% of offsets can come from outside California. This has created great uncertainty for offset projects in general and CMM and VAM projects more specifically. As there is no coal mining in California, all CMM and VAM projects would be located outside California. With respect to reducing the total volume of offsets allowed into the market, VAM projects are at a disadvantage because the development lead times are long, costs are high, and implementation of many projects could overwhelm the market.
- *To address legal/policy barriers:*
   - *Prepare a policy paper analyzing the impact of the California Cap-and-Trade program on the development of VAM projects in the U.S. surveying the mining industry, project developers and buyers of carbon credits. The purpose would be to identify those aspects of the Cap-and-Trade that are successful in encouraging implementation of VAM projects while also identifying disincentives.*
   - *Prepare a comparative policy analysis providing an update and review of regulatory and market drivers across major mining countries with an assessment of what has worked and what hasn't worked.*

Market/economic barriers to VAM deployment

- VAM oxidation projects have high capital and operating expenses requiring significant up-front capital and many years of operation before payback is achieved.
- VAM manufacturers have little interest in further R&D to improve designs and reduce costs without the existence of confirmed markets. Most likely, improvements will made through continued R&D by organizations such as CSIRO or by manufacturers working on commercial projects.
- For abatement-only projects, the only revenue source is from carbon credits or avoidance of carbon taxes or penalties. The high capex and opex combined with exposure to government-determined markets results in considerable risk exposure for project developers. In some

cases, project developers, investors and coal mine owner/operators prefer to invest in addressing other GHG sources such as gas drainage, coal combustion,

- Where possible, it may be more effective to invest in increased gas drainage, even when not required for safety. This could include drilling additional pre-mining and post-mining boreholes, or increasing drainage time. It could also entail improving gas capture through better goaf sealing, pressure balancing, improved borehole sealing, more effective regulation of vacuum pressure in the drainage system, or even potentially reconfiguring the ventilation system. The objective would be to increase the quality and quantity of drainage gas where a range of end-use technical options and experience already exist while conversely decreasing the methane emissions into the mine ventilation system. The mine gas emissions would effectively remain the same, but the balance between mine ventilation and gas drainage would shift. This idea was also raised during the first VAM discussion in Geneva in September. Although this idea generated interest and discussion among the participants, several key points were raised:
    - This would still not be 100% effective.
    - Installation and operation of gas drainage systems, especially in-mine drainage, must coordinate with the development of entries and headgates/tailgates and mining of the longwalls. Additional boreholes, longer drainage time, etc may delay mine development and add costs to the core business of the mine.
    - In China, drainage is often required even if it is not necessary because CH_4 concentrations are often low. Investing in VAM mitigation can be more practical. Drained gas can enrich the VAM increasing the average concentration and making power generation and heat recovery more realistic. However, it was emphasized in the discussion that even when enrichment is more economic, good practice should be to keep minimum CH_4 concentrations above 30% and away from the explosive range.
- Although many participants focused on VAM use primarily as GHG abatement, several other participants strongly encouraged the participants to think of VAM as an energy resource. Notably, in China, this is how VAM is coming to viewed, especially with efficiency improvements in steam turbines.
- A critical need is access to reliable data on VAM emissions including air flow and CH_4 concentrations on a mine-specific and shaft-specific basis. Such data will provide essential information on the resource and the potential for emission reductions and will also support more accurate assessment of marginal abatement costs and project opportunities. Although some countries, including the Australia and the U.S. have good data on VAM emissions, reliable data is very difficult to access in many other countries. Even where data exist, it is often not publicly available. The U.S. is an exception where data reported to the GHGRP, including shaft-specific air flows and CH_4 concentrations, are made available to the public.
- New or improved VAM abatement technologies with simple processes, lower energy consumption, and excellent tolerance with dust contained in ventilation air to substantially reduce capital, operational and maintenance cost
- *To address market/economic barriers:*
    - *Prepare a global VAM resource assessment summarizing mine-specific opportunities.*
    - *A marginal cost study was proposed based on input from the first Dialogue in September. The study would consider the marginal cost of implementing VAM projects*

versus the cost of increased gas drainage. There was some interest in this proposed concept, but there were also some concerns that were raised.

- *Any marginal cost study would most likely be site-specific. The mining operations and mining conditions at each mine are unique. The marginal cost of gas drainage and VAM project implementation at the study mine may not be reflective of the ability to implement these projects, the associated costs of doing so or the ensuing results that would be achieved at operating mines.*
- *The costs of possible delays in mine development and longwall production due to more extensive gas drainage or longer drainage times would have to be considered in the economic analysis.*
- *In some cases, even increasing gas drainage will not change the volume of methane emitted from mine ventilation shafts. The reduction in in-situ gas content (pre-drainage) or gas emissions into the mine (post-drainage) will result in increased advance rates and increased coal production with the end-result being VAM emissions remain steady and total gas liberated from the mine (VAM + drainage) increases.*

Messaging

- The last point of discussion was effective messaging. VAM is a major source of GHG emissions, especially in major coal mining countries, yet VAM abatement has limited visibility.
- Some participants commented that the coal industry and other stakeholders have not succeeded in developing and conveying a clear vision to advance VAM use even though the potential advantages of VAM emission reductions can underpin a very strong message.
  - In particular, several participants noted the challenges in securing finance for VAM projects given the negative reaction that international and bilateral financial institutions have with respect to coal. Rather than seeing VAM and CMM projects as environmentally, socially and economically beneficial, the financing organizations take a negative view of any association with coal, some even incorrectly assuming that revenues from VAM and CMM projects will extend the life of coal mines – that some owner/operators are mining coal to generate carbon credits.
- There are several key advantages to VAM abatement vis-à-vis other abatement strategies.
  - The magnitude of emissions is very large on a facility-specific basis. In the U.S., for example, on a nation-wide basis underground coal mines reporting to the Greenhouse Gas Reporting Program (GHGRP) produce just less than half the GHG emissions (CH_4, CO_2, N_2O) of Oil & Gas Onshore Production facilities reporting to the program, yet in 2016 there 94 coal mines reporting and 512 oil and gas facilities. Further, an oil and gas facility is defined as all operations of an owner/operator in an entire basin covering a significantly larger geographic area than a coal mine.[8]
  - The number of facilities and point sources at coal mines is limited compared to some other more diffuse methane and GHG sources. In the U.S. example, the 94 coal mines

[8] Talkington, Clark, Kyeong Pil Kong, & Felicia Ruiz (2018). Achieving near-zero methane emissions coal mining. 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14. Melbourne, Australia. October 2018.

    - only had 764 emission points whereas there were almost 1.5 million sources within the oil and gas onshore production segment.[9]
    - Emission baselines are relatively easy to establish for VAM projects.
    - Emissions and emission reduction are measurable and verifiable with reasonable accuracy and with monitoring equipment available today.
    - Where CH_4 concentrations meet technical limits, technologies are available, have been field tested and commercially demonstrated.
    - All emission reductions are considered to be fully "additional." There has never been any question about the additionality of VAM projects.
    - The principal GHG associated with VAM is CH_4 which as a GWP of 28-34 times that of CO_2 over a 100-year time frame but a much higher GWP in the shorter term due to its atmospheric life.
    - Capture and recovery of the large volumes of CH_4 emitted from ventilation shafts also present a considerable energy resource.
- Another important message is that VAM abatement can make an important contribution to reducing the coal industry environmental footprint, i.e., greening the industry.
    - VAM abatement is not a substitute for any other action, but part of a portfolio of actions that can be taken within the coal supply chain to reduce the industry's impact on climate change.
    - Reduction of VAM emissions will not substitute for the very large potential of Carbon, Capture, Storage & Utilization (CCUS) or coal combustion emission reductions, but it can serve as an effective bridge while CCUS comes into commercialization. The largest VAM projects in operation today are delivering emission reductions equivalent to the early stage commercial CCUS projects.[10]
- The issue of "messaging" and ways to remedy it have been discussed extensively within the GMI Coal Subcommittee and the UNECE Group of Experts on CMM. However, these discussions have note yielded a coherent strategy or campaign.
- *To address effective messaging:*
    - *An effective briefing paper and outreach campaign could be developed followed by direct outreach to the investment community and policymakers.*
    - *A China-based case study could be developed evaluating the social impacts, economic impacts and environmental impacts of VAM projects.*

[9] Talkington, Kong & Ruiz (2018)
[10] Talkington, Kong & Ruiz (2018)

Appendix A

Agenda for the Expert Dialogue on VAM
25 October 2018

CSIRO and the Global Methane Initiative

Expert Dialogue on Ventilation Air Methane (VAM)

Melbourne Convention and Exhibition Centre (MCEC)
25 October 2018

14:00-14:10 Welcome & opening remarks
Dr. Hua Guo
Research Director - Coal Mining Research Program
Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Ms. Felicia Ruiz
Co-Chair, Coal Subcommittee, Global Methane Initiative
United States Environmental Protection Agency (U.S. EPA)

14:10-14:15 Introduction of participants

14:15-14:25 Update on global VAM emissions and VAM abatement projects
Mr. Richard Mattus
President, RM Consulting

14:25-14:40 Current status of VAM abatement science and technology
Dr. Shi Su
Coal Mining Research Program
Commonwealth Scientific and Industrial Research Organisation (CSIRO)

14:40-14:50 Coal industry perspective on VAM abatement
Mr. Jim Craigen
ACA Low Emissions Technologies Ltd (ACALET)

14:50-16:10 Facilitated discussion: technical, market and policy issues affecting VAM technology and project development
Dr. Sarah Cleary
Business Development and Commercial Manager
Commonwealth Scientific and Industrial Research Organisation (CSIRO)

16:10-16:30 Break

16:30-17:50 Facilitated discussion (continued)

17:50-18:20 Conclusions and possible action items
Dr. Sarah Cleary, CSIRO

18:20-18:30 Wrap-up, conclusions and next steps
Dr. Hua Guo, CSIRO
Ms. Felicia Ruiz, U.S. EPA

Appendix B

List of Participants

Expert Dialogue on Ventilation Air Methane
25 October 2018
Melbourne, Australia

List of Participants

Sarah Cleary, Ph.D., MIPLaw
Business Development and Commercial Manager
CSIRO
Australia

Jim Craigen
Deputy Director Technology
COAL21 Fund
Australia

Hua Guo, Ph.D.
Research Director - Coal Mining Research Program
CSIRO Energy
Australia

Yonggang Jin, Ph.D.
Team Leader
CSIRO Energy
Australia

Ben Klaassen
Principal Environment A&I
Minerals Australia, HSE
BHP
Australia

Dr Jamie Knight
Senior Project Officer - Science, Coal Innovation NSW
Division of Resources and Geoscience
Australia

Richard Mattus
RM Consulting Ltd
Sweden

Alex Neels
Manager, Energy & Emissions
Peabody Australia
Australia

Mel Round
Assistant Manager, Low Emissions Section
Onshore Minerals, Resources Division
Department of Industry, Innovation and Science
Australia

Felicia Ruiz
U.S. Environmental Protection Agency Climate Change Division
Co-Chair, Coal Subcommittee, Global Methane Initiative
United States

Shi Su D.E. (Thermal Energy), Ph.D. (Chemical Engineering)
Senior Principal Research Scientist
CSIRO Energy
Australia

Trevor Stay
General Manager Gas
Anglo American
Australia

Sun Dongling, Ph.D.
Director, Division of Coal Mine Gas Research
Chongqing Research Institute
China Coal Technology Engineering Group
China

Clark Talkington
Vice President
Advanced Resources International, Inc.
United States

Steven Wan, Ph.D.
Chief Executive Officer
Fortman (Beijing) Clean Energy Technology Ltd.
China

Elize Wium
A/g Assistant Manager, Low Emissions Technology
Onshore Minerals, Resources Division
Department of Industry, Innovation and Science
Australia