Coal Mine Methane Recovery and Utilization Technologies

Development Trends and Outlook

Report / November 2024

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The contents of this report do not represent the views of the above experts and institutions or those of the project proponents.

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China University of Mining and Technology-Beijing (CUMTB) is a national key university under the Ministry of Education, recognized as part of the "Double First-Class" initiative and a founding member of the Strategic Alliance of Industrial Technology Innovation. With a history dating back to 1909, CUMTB specializes in energy-related disciplines, excelling in Mining Engineering and Safety Science. It is a leader in innovative research, producing significant advancements such as China's first mining robot and major breakthroughs in coal-to-oil technologies. The university collaborates extensively with international and domestic partners, supporting the energy sector's high-quality development.

Table of Contents

Introduction

China's industries are actively advancing the energy transition and industrial upgrading to meet the country's ambitious goals of carbon peaking and carbon neutrality. In 2023, clean energy accounted for 26.4% of China's total energy consumption, an increase of 10.9% over the span of a decade. Simultaneously, China led the world in green energy supply for several years, with installed capacity of renewable energy comprising about 40% of the global total. As of the end of July 2024, China's combined wind and solar power capacity reached 1.2 billion kilowatts, achieving its planned target 6 years ahead of schedule. While clean energy is expanding rapidly, traditional fossil fuels continue to be part of the energy system and underpin social and economic development. Coal companies are increasingly engaged in green technology innovation, optimizing energy management, and pursuing ecological restoration and resource utilization, to reduce their carbon emissions.

As one of China's key initiatives for carbon emissions reduction in coal production, coal mine methane (CMM) recovery and utilization has yielded remarkable results with the support of government policy. The gaseous substance associated with the coal production process, commonly known as CMM, is similar to conventional natural gas with methane as its main component. Recovering and utilizing CMM as an energy source not only supplements energy supply, enables resource utilization, and delivers economic value, but it also directly reduces fugitive emissions from coal production, providing an effective way to avoid methane emissions in the short term. In light of the considerable climate, energy, and economic benefits of CMM recovery and utilization, China has adopted an array of policies to accelerate the development of CMM technologies since the 11th Five-Year Plan period (2006–2010). As a result, the amount of CMM utilized has increased steadily, playing a positive role in methane emissions control.

China continues to introduce methane emissions control targets and policies, unlocking the potential for further development of CMM recovery and utilization. The Methane Emissions Control Action Plan jointly released by several ministries and commissions in 2023 identifies CMM recovery and utilization as one of the key actions of methane emissions control in the energy sector. In July 2024, the Ministry of Ecology and Environment solicited opinions on the Methodology of Voluntary Greenhouse Gas Emissions Reduction Projects: Utilization of Low-Concentration Drainage Methane and Ventilation Air Methane in Coal Mines. These policies have unlocked new opportunities for the CMM utilization market while also creating development prospects for technologies that, despite having significant potential, face challenges in terms of economic viability, technological maturity, and market acceptance.

RMI and China University of Mining and Technology (Beijing) have jointly written this report to enable policymakers, enterprises, investors, and other stakeholders to better identify the potential and possibilities of CMM recovery and utilization. The report analyzes and explores the status of China's CMM technology and its recovery potential, while offering an outlook on the maturity, cost, and investment needs of CMM technology in China and suggestions for next steps. It aims to provide a reference for relevant market participants and policymakers.

Coal Mine Methane (CMM) Recovery and Utilization: A Positive Initiative for Coal Producers to Reduce Emissions

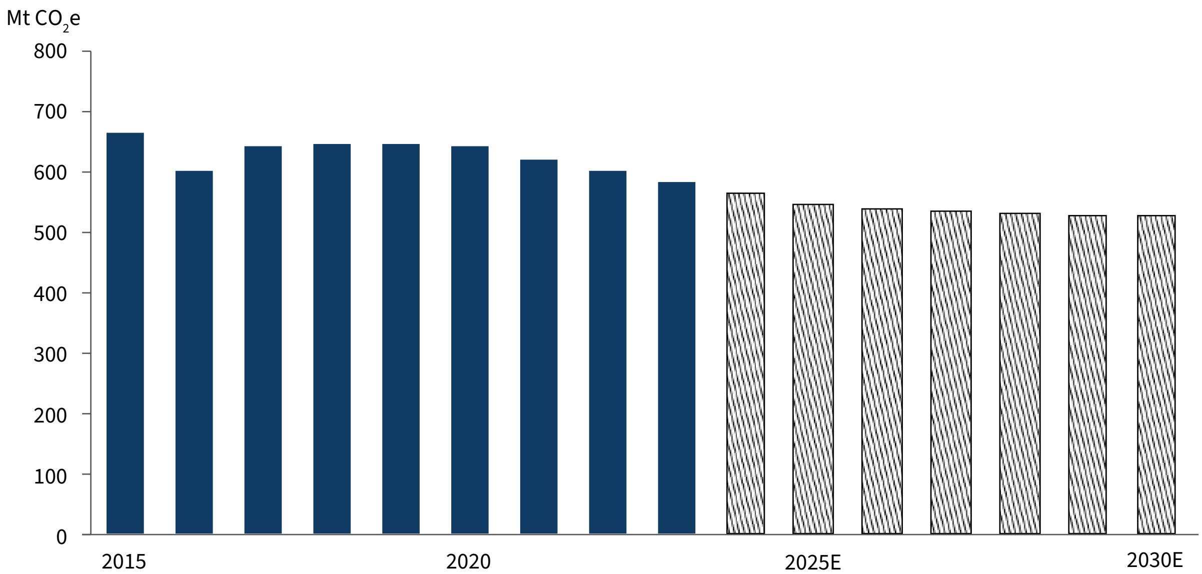
Coal Production Is a Source of Greenhouse Gas (GHG) Emissions

As China's primary energy source, coal has long provided as solid foundation for the country's economic and social development. China has a large demand for coal and has thus maintained a high level of coal production and consumption. Since 1980, the share of coal in primary energy production and total energy consumption has been over 55%, supporting key industries such as power, steel, construction materials, and chemicals. In the context of carbon neutrality, China is actively promoting the transition to new and clean energy sources, while strictly and rationally controlling the total coal consumption.
As coal consumption in key industries has plateaued, the share of coal production and consumption has leveled off or declined. In 2023, coal accounted for 67% of total primary energy production in China down from 77.4% in 2005. Although total energy consumption increased significantly between 2005 and 2023, the portion provided by coal decreased from 72.4% in 2005 to 55% in 2023.[1]

Coal production in China is a source of GHG emissions. Coal production involves coal mining, processing, storage, and transportation, which generate carbon dioxide emissions from the combustion of fossil fuels in stationary and mobile equipment and fugitive methane emissions from coal mining and post-mining activities. In 2023, the total GHG emissions from coal production was about 600 million tons of CO_2e in China (Exhibit 1). Emissions from coal production are higher than other key energy-intensive industries — 50% higher than those from aluminum and 220% higher than from ammonia production, for instance. Emissions from coal production account for 47% of cement industry emissions and 40% of those generated by the steel industry. With coal's significant share in China's greenhouse gas emissions, reducing production-related emissions is crucial to achieving China's carbon peaking and carbon neutrality goals.

Emissions from coal production will continue to decline. Coal reserves and policies will promote the centralization of coal production in China, optimizing production and transportation. By 2030, emissions from coal production are expected to decrease 20% from 2020 levels, to around 500 million tons CO_2e. Implementing emissions reduction initiatives in the coal production process will help China achieve its carbon peaking and carbon neutrality goals.

Exhibit 1 **Estimated emissions from coal production in China**



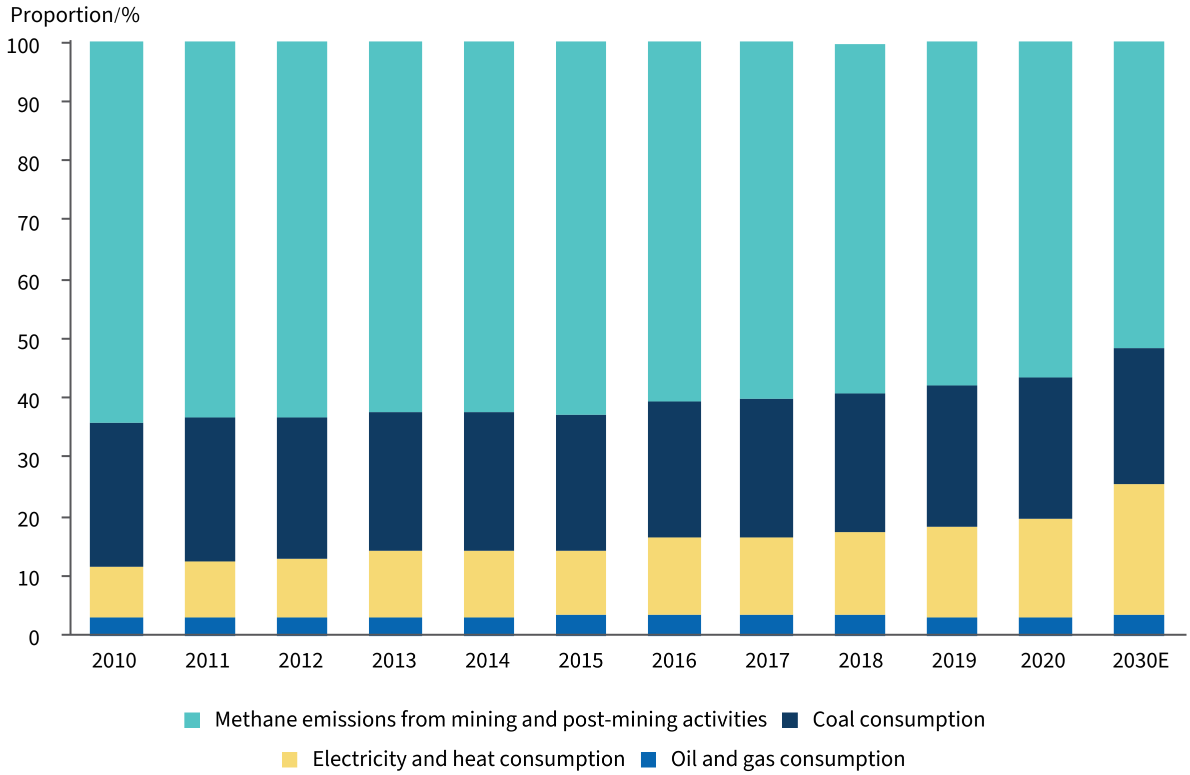
RMI Graphic. Source: Journal of Natural Resources, https://www.jnr.ac.cn/CN/10.31497/zrzyxb.20190303, and RMI analysis.

CMM Recovery and Utilization Is a Key Means of Reducing Emissions from Coal Production

The primary GHG emitted in coal production, and the focus of emissions reduction in the process, is methane. Most GHG emissions in coal production are from energy consumption and fugitive emissions. Energy consumed in coal production mostly comes from raw coal, oil, gas, and electricity and heat, creating emissions primarily in the form of carbon dioxide, which accounts for about 40% of total GHG emissions from the process. Fugitive emissions, from the escape of methane during activities such as coal extraction, washing, transportation, and storage, constitute a significant portion — as much as 57%[2] of the total by some estimates — and thus are a primary target for emissions reduction (see Exhibit 2). In addition, methane is slowly released from underground coal mines for the 10 to 30 years after they are decommissioned. Currently, China has as many as 10,000 closed coal mines, and this number may increase to 15,000 by 2030,[3] so methane emissions reduction from abandoned mines is also an area worth tracking.

CMM recovery and utilization is a key means of reducing emissions in coal production. Methane emissions from coal production can be effectively recovered and utilized through technical means. CMM, like conventional natural gas, can be combusted as a fuel. In this process, methane is oxidized into carbon dioxide and water, while releasing heat for power generation and heating. Methane has a global warming potential 28 times that of carbon dioxide over a 100-year period, so CMM recovery and utilization can significantly reduce the climate impact from coal production. At the same time, the electricity and heat generated can replace coal-fired boilers and other facilities in coal mines, further reducing carbon dioxide emissions from on-site coal consumption.

Exhibit 2 Sources of GHG emissions from coal production in China



Note: Emissions from production include the process by which raw coal is extracted from underground or surface coal mines and washed to become a coal product, but not emissions from abandoned mines.
RMI Graphic. Source: Advanced Engineering Sciences, **http://jsuese.cnjournals.com/html/2022/1/202100924.html**

CMM Recovery and Utilization Delivers Multiple Benefits

While reducing GHG emissions, CMM recovery and utilization offers multiple benefits including:

- **Energy benefits:** CMM contains the same main component, methane, as conventional natural gas. At appropriate concentrations, it can be used directly as natural gas to replace coal. Every 1,000 cubic meters (m^3) pure CMM recovered and utilized is equivalent to saving 1.2 tons of standard coal equivalent (tce).

- **Economic benefits:** Electricity and heat generated by CMM utilization can replace coal consumption in mines and reduce the need for purchased electricity, thereby lowering operating costs for mines. Additionally, surplus electricity, heat, and gas can be sold to supply energy to other regions, generating profits.

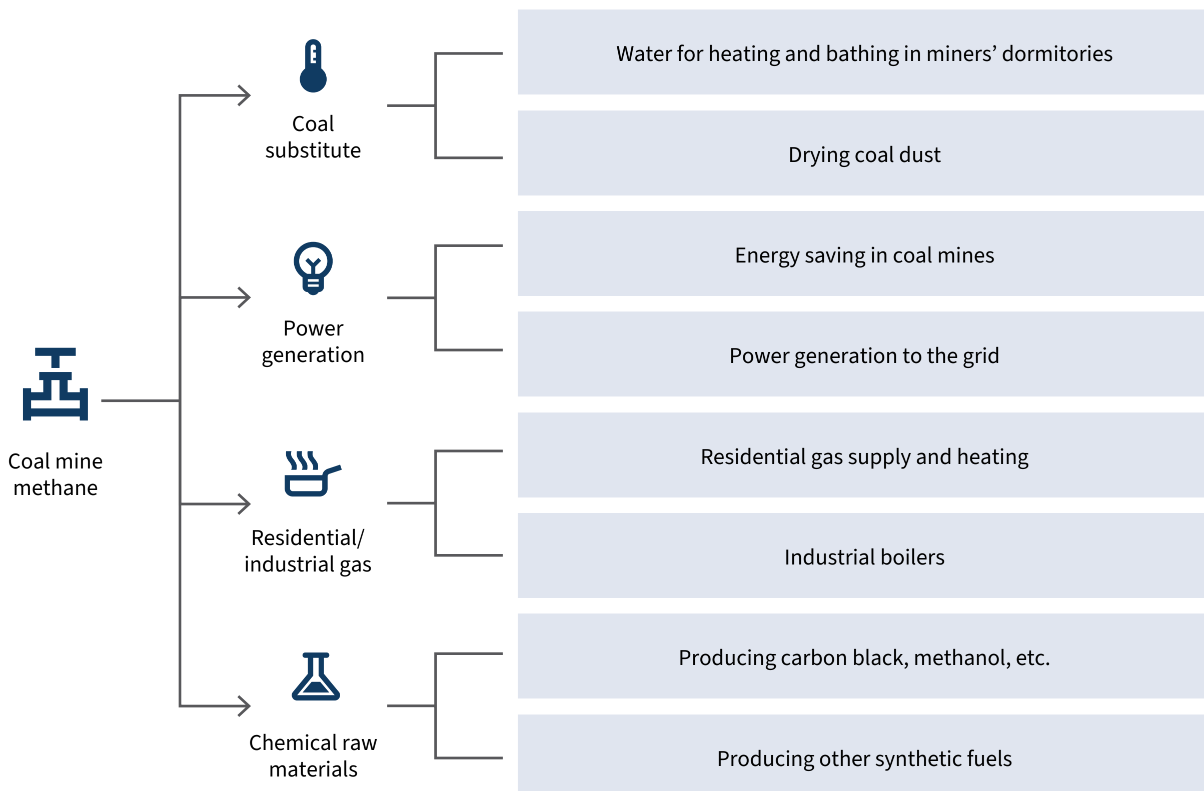
- **Safety benefits:** CMM recovery and utilization can effectively reduce the risk of gas explosion and minimize production stoppages caused by excessive gas concentrations, thereby significantly improving the safety and operational stability of the mine.

- **Other social benefits:** Methane is not only a potent greenhouse gas, but also a precursor to ozone. CMM utilization can reduce methane emissions and thus reduce ozone growth, benefiting human well-being and food production. The construction and operation of CMM projects also create new jobs in the local community, helping with the re-employment of miners.

CMM utilization can offer coal mines several economic benefits (see Exhibit 3) including:

- **Energy saving in mining areas:** Utilizing CMM to replace coal within the mining area allows for local recovery and utilization. It can be used to provide heat and hot water at the mine and its facilities, and provide insulation for underground mine shafts thereby reducing coal consumption and the need for purchased heating.
- **Electricity and heat sales:** CMM can be used to generate electricity or steam. The electricity can be sold to the grid, and steam can be supplied through pipelines to heat the surrounding areas.
- **Direct sale of pipeline gas:** CMM with higher concentrations can be utilized as unconventional natural gas, delivered to the neighboring residential areas for cooking and heating or through pipelines to factories as fuel for industrial boilers.
- **Chemical raw material gas:** Highly concentrated CMM can be used as chemical raw material to produce carbon black, methanol, and other products.

Exhibit 3 **Main utilization methods of CMM**



RMI Graphic.

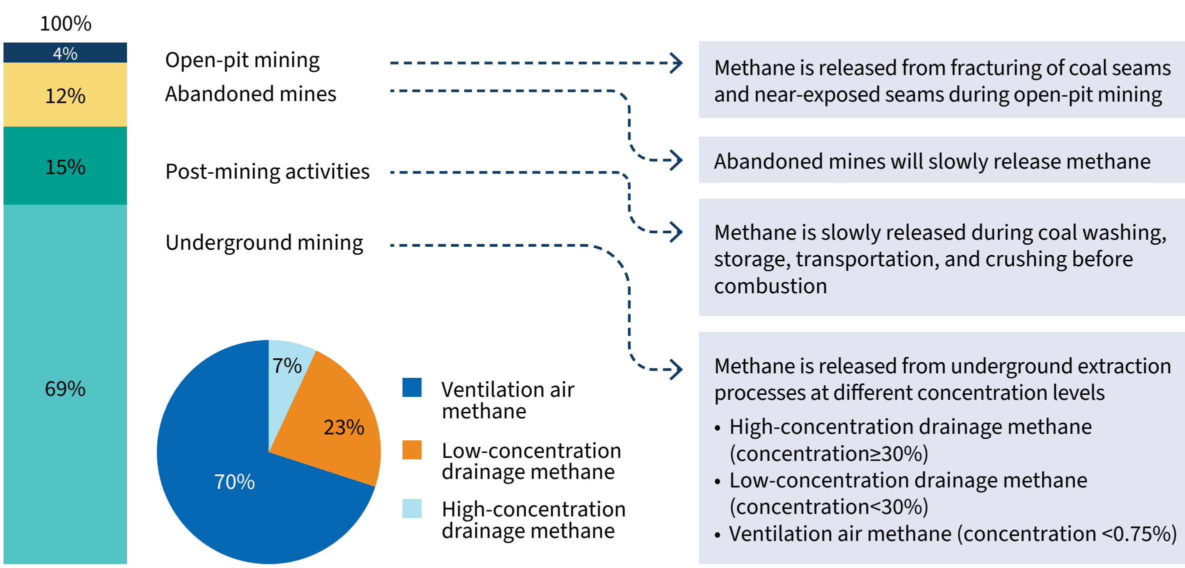
Status of CMM Recovery and Utilization

China Has Established a Technology System for CMM Recovery and Utilization

CMM emissions during coal production mainly originate from coal mining, post-mining activities, and abandoned mines. During the mining process, coal seams are fractured, releasing CMM that was stored in the seams into the atmosphere. Coal mining can be divided into open-pit (surface) mining and underground mining. The gas generated by open-pit mining escapes directly into the atmosphere without going through pipelines, while the gas generated by underground mining is transported to the surface through the drainage system and ventilation systems. The mining process does not release all CMM. Remaining gas that is slowly released from the coal during subsequent processing, storage, and transportation activities is considered emissions from post-mining activities. In addition, coal mines may continue to release CMM through natural or anthropogenic pathways for a period of time after decommissioning[4], leading to both resource waste and an increase in GHG emissions.

CMM generated by underground mining can be collected through the ventilation and drainage systems. CMM collected through the ventilation system is called VAM with a concentration of 0%–0.75%, while the concentration of drainage methane is generally 0%–90%, which can be transported to oxidation facilities for utilization. By contrast, methane emissions produced from surface mining and postmining activities are diffuse and difficult to recover with existing technologies. Methane from abandoned mines can also be recovered using technical methods. Gas in well-sealed abandoned mines can be extracted after closure, with methane concentrations ranging from 15% to 90%.[5] The gas extracted from abandoned mines can be utilized in a similar way to that from underground mines. But unlike active underground mines, CMM extraction from abandoned mines requires greater investment to address greater complexity and issues related to mine rights and gas ownership. In China, most methane emissions from coal production — over 70% — come from underground mining, while emissions from abandoned mines account for 12%. These sources are crucial for the recovery and utilization of methane (see Exhibit 4).

Exhibit 4 **Main sources of methane emissions in China's coal sector**



RMI Graphic. Source: Journal of China Coal Society, https://www.mtxb.com.cn/cn/article/Y2022/I1/470; and Resource Science, https://www.resci.cn/CN/10.18402/resci.2020.02.10, data are from RMI estimates.

Western countries were the first to initiate CMM recovery and utiliztion, with technologies for recovering high-concentration CMM and VAM reaching a relatively mature stage. The development of methane recovery technology began in the 1960s, driven by the energy crisis, with early trials conducted by mining-developed countries such as the United States, Russia and Australia. During the 1980s and 1990s, the technology for power generation from burning high-concentration CMM gradually advanced, resulting in substantial investments. In the 21st century amid the global focus on greenhouse gas reduction, the utilization of VAM has gained increasing attention, with Australia's development of VAM oxidation technology serving as an example. In the context of carbon neutrality, major coal-producing countries are intensifying their efforts to implement methane recovery and utilization technologies. Supported by international policies like the Clean Development Mechanism (CDM), projects for extracting methane and utilizing VAM have been rapidly promoted.

Since the 11th Five-Year Plan, China has been continuously advancing its CMM recovery and utilization technology. Years of continued effort have led to diverse utilization methods, creating a graded CMM utilization technology system.[6] CMM can be oxidized as a fuel for heating and power generation, used in residential and industrial settings, and purified into liquified natural gas (LNG) or compressed natural gas (CNG). The development of these technologies has laid a solid foundation for the implementation of CMM recovery and utilization projects (see Exhibit 5).

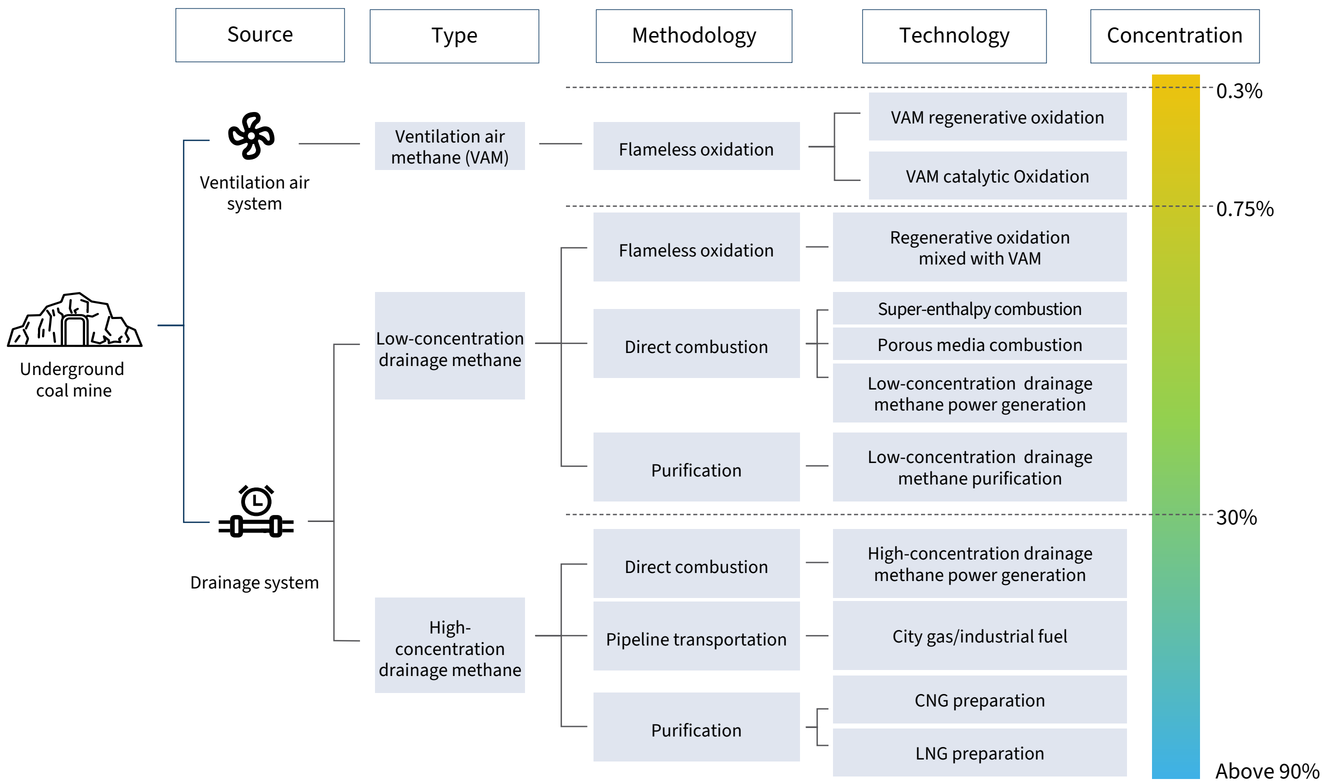
Reasonable selection of technologies (see Appendix for detailed principles of each technology) is required for gas generated in underground coal mines based on sources and concentrations. These technologies can be broadly grouped into the following three types:

- **VAM**, where the methane volume fration is typically < 0.75%, can be utilized if the methane concentration is above 0.3%. The main applicable technology is flameless oxidation, where methane is oxidized by controlling the temperature and oxygen concentration of the reaction zone without evident flame.[7] It is further classified into regenerative ventilation air oxidation method and catalytic ventilation air oxidation method. Additionally, VAM can be mixed with drainage methane (2%–8%) to increase the overall methane concentration to around 1.2%, after which flameless oxidation can also be performed.

- **Low-concentration drainage methane,** with a methane volume fraction <30%, is generally used to produce hot steam and electricity by direct combustion instead of being transported through long-distance pipelines. Drainage methane with a concentration of less than 8% can be oxidized to produce saturated steam through techniques such as super-enthalpy combustion and porous media combustion; and drainage methane with a concentration of more than 8% can be oxidized using internal combustion units for power generation. In addition to direct combustion, low- concentration drainage methane can also be purified and concentrated using technologies like pressure swing adsorption, making its utilization more flexible as the concentration increases.

- **High-concentration drainage methane**, with a methane volume fraction ≥30%, features high methane concentration and flexible utilization. It can be directly used for gas-fired power generation or transported via pipelines to nearby areas for use as city gas or industrial fuel. Additionally, high-concentration methane can be purified to produce LNG and CNG, with the purified gas reaching a methane concentration of up to 98%.

Exhibit 5 CMM recovery and utilization system for underground coal mines in China



RMI Graphic.

The development of low-concentration gas recovery and utilization technology in China has made substantial progress internationally. Although China's work in this area began in the early 21st century—later than in Western countries—after more than 20 years of efforts and exploration, China's methane recovery and utilization technology has now reached an advanced level. Currently, China is keeping pace with international standards in key areas such as high-concentration CMM power generation and VAM oxidation. China has also made advancements in technological innovation for methane recovery and utilization, particularly in low-concentration CMM purification, concentration, direct combustion, and power generation technologies (as shown in Figure 6). Development in methane recovery and utilization for abandoned coal mines has been slower, but assessments of gas sources and occurrences in some abandoned mines have begun, alongside ongoing research into related recovery technologies, which remain in the early stages.[8]

Exhibit 6 Development Status of CMM Recovery and Utilization Technology

Technology	Development Status		Role	Representative enterprises/ organizations (in no particular order and non-exhaustive)	
	China	Global		China	Global
Regenerative oxidation of VAM	★★★	★★★	Peer	山东胜动新能源科技有限公司	DÜRR; ANGUIL 恩国
Catalytic oxidation of VAM	★★	★★	Peer	浙江亿扬能源科技有限公司; YUREENT 昱昌环境	CSIRO Australia's National Science Agency; CanmetÉNERGIE VARENNES
Mixing oxidation of VAM + low-concentration drainage methane	★★★	★★	Leader	扬德环能 YONDER ECOENERGY	EISENMANN; CanmetENERGY
Super-enthalpy combustion of low-concentration drainage methane	★★	–	Leader	山西高创能源新技术有限公司; Beijing Junfa Co	—
Porous media combustion of low-concentration drainage methane	★★	–	Leader		
Low-concentration drainage methane purification	★★	★	Leader	四川省达科特能源科技股份有限公司; 中国煤炭科工集团	Japan Gas and Power Company
Low-concentration drainage methane power generation	★★★★	★★★	Leader	山东胜动新能源科技有限公司 Shandong Shengdong New Energy Technology Co., Ltd	MWM Energy. Efficiency. Environment.; DEUTZ
High-concentration drainage methane power generation	★★★★★	★★★★★	Peer		INNIO; CAT
LNG and CNG preparation with high-concentration drainage methane	★★★★	★★★★	Peer	四川省达科特能源科技股份有限公司; 中国煤炭科工集团	SwRI SOUTHWEST RESEARCH INSTITUTE
High concentration drainage methane pipeline transportation	★★★★	★★★	Peer	晋能控股煤业集团 JINNENG HOLDING COAL INDUSTRY GROUP	WARRIOR; CONSOL ENERGY
Abandoned mine methane power generation	★	★★	Follower	淮河能源 HUAIHE ENERGY	Vessels Carbon Solutions Inc.; GreenGas

RMI Graphic. Source: RMI Analysis

China Has Initially Developed Policies for CMM Recovery and Utilization

CMM, which occurs naturally with coal deposits, explodes when in contact with an open flame when its methane concentration reaches 5%–16%. This constitutes a safety hazard in coal mines. As an unconventional natural gas, CMM can serve as a high-quality energy and chemical feedstock. China places great emphasis on the prevention of CMM explosions and the recovery of CMM. Since the 11th Five-Year Plan period (2006–2010), a series of policies and measures have been implemented to improve the extraction and utilization of CMM, accelerate the development of CMM industry, ensure safety in coal mining operations, and increase the supply of clean energy (see Exhibit 7).

From the 11th Five-Year Plan to the 13th Five-Year Plan period (2006 to 2020), Chinese policies on CMM recovery were aimed at ensuring coal mine safety, facilitating resource recycling, and reducing climate and environmental pollution. The National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) issued strategic planning policies for the development and utilization of coalbed methane and coal mine gas,[i] defining the underground drainage methane extraction and utilization targets for 2010, 2015, and 2020, based on the 11th, 12th and 13th Five-Year Plans. These policies also clarified the planning requirements for the construction of large-scale mining areas for CMM extraction in key regions and demonstration projects for CMM utilization. The tax subsidy policy was based on the feed-in tariffs for power generation from CMM and subsidies for the development and utilization of CMM, supported by measures such as tax exemption for projects involving the development and utilization of CMM. Some provinces have also increased their subsidies on top of national policies. For example, Shanxi Province and Shaanxi Province added RMB 0.1/m^3 to the central government's subsidy for the extraction and utilization of CMM, and Hunan province awarded RMB 0.8–1 million for each newly built CMM power plant. Additionally, the Ministry of Ecology and Environment issued the Emission Standard of Coalbed Methane/Coal Mine Gas (Interim) (GB 21522—2008) in 2008, which prohibits coal mines from emitting methane with a concentration over 30% into the atmosphere.

In recent years, China has accelerated its efforts to control methane emissions by developing and revising policies and measures. In 2023, the Ministry of Ecology and Environment and 10 other ministries and commissions jointly released the Methane Emissions Control Action Plan, which outlines a series of key tasks for methane reduction in the energy sector. This plan encourages and guides coal enterprises in the extraction and utilization of CMM, with the goal of reaching an annual utilization of 6 billion cubic meters (bcm) by 2025, and further increase utilization by 2030. In 2024, the Ministry of Ecology and Environment revised the Emission Standard of Coalbed Methane/Coal Mine Gas, limiting the concentration of emitted methane to 8%, down from the original 30% allowed. The updated standards also suggest that drainage methane with a concentration below 8%, as well as ventilation air methane (VAM), should be explored for comprehensive utilization, if safety can be ensured.

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i The definition and terminology of CMM vary across countries and regions. In this report, the definition and source of CMM are aligned with those of the US Environmental Protection Agency (see https://www.epa.gov/cmop/sources-coal-mine-methane). In China, the definition of coal mine gas mainly follows the 'Terms Related to Coalbed Methane (Coal Mine Gas)' (GB/T 31537—2015), referring to the gas mixture primarily composed of methane that escapes from the coal and surrounding rock in a mine.

Exhibit 7 Major policies and measures on CMM recovery and utilization in the coal industry

2005

National Development and Reform Commission

Eleventh Five-Year Plan for the Development and Utilization of Coalbed Methane (Coal Mine Gas)

- By 2010, extract 5 bcm drainage methane annually from underground mines across the country, with an extraction rate of over 40%; utilize at least 3 bcm, or more than 60%, of extracted drainage methane.
- Gradually establish an industrial system for the development and utilization of CMM.
- Construct CMM management and utilization demonstration projects.

2006

Ministry of Finance and Other Departments

Notice on the Exemption of Import Taxes on Imported Materials for Coalbed Methane Exploration and Development Projects

2006

General Office of the State Council

Opinions on Accelerating the Extraction and Utilization of Coalbed Methane (Coal Mine Gas)

- Land for the construction of CMM extraction and utilization projects shall be prioritized in accordance with state regulations.
- If treated CMM reaches the defined quality standards, it can be prioritized to incorporate into the natural gas pipeline network and urban public gas supply pipeline network.
- Coal mine enterprises are allowed to generate and use electricity produced from CMM; power grid enterprises should give coal enterprises priority to sell excess electricity to the grid (if applicable).
- Governments at all levels should secure funds to provide financial support or preferential loans for CMM extraction and utilization projects

2007

National Development and Reform Commission

Notice on the Implementation of Opinions on the Utilization of Coalbed Methane and Coal Mine Gas for Power Generation

- Feed-in tariffs for CMM power plants are set against the feed-in tariffs for biomass power generation projects in the Trial Measures for the Management of Renewable Energy Power Generation Prices and Cost Sharing developed by the National Development and Reform Commission.

Ministry of Finance

Implementing Opinions on Subsidizing the Development and Utilization of Coalbed Methane (Coal Mine Gas)

- The central government subsidizes CMM enterprises at the rate of RMB 0.2 per m^3 of (pure) CMM; local governments may provide additional subsidies for the development and utilization of CMM according to local conditions.

Ministry of Finance

Notice on Issues Concerning Tax Policies for Accelerating Coalbed Methane Extraction

- Value-added tax on the extraction and sale of CBM shall be first collected and then refunded. If the refunded tax is used to explore CBM technology and expand CBM production, the enterprise income tax shall be exempted.

2008

Ministry of Ecology and Environment

the Emission Standard of Coalbed Methane/Coal Mine Gas (Interim) GB 21522-2008

- CBM emission is prohibited in CBM surface development systems.
- It is prohibited for coal mine drainage systems to emit high-concentration CMM with methane volume fraction ≥30%.
- For high-concentration CMM that can be directly utilized, gas storage tanks shall be established with supporting gas utilization facilities. The gas can be used for civil use, power generation, chemical industry applications, and other purposes.
- High-concentration CMM that cannot be utilized can be dealt with by flaring or other means.

2011

State Administration of Taxation

Notice on the Taxation Policy on Materials Imported for Coalbed Methane Exploration and Development Projects during the Tenth Five-Year Plan Period

State Administration of Work Safety and others

Interim Provisions on Compliance of Coal Mine Gas Extraction

2011

National Development and Reform Commission

Twelfth Five-Year Plan for the Development and Utilization of Coalbed Methane (Coal Mine Gas)

- By 2015, extract 14 bcm of underground drainage methane annually and utilize more than 60%.
- Installed capacity of gas power generation exceeds 2.85 million kW, supplying over 3.2 million households.
- Build 36 at-scale CMM extraction and utilization zones with an extraction capacity of more than 100 million m^3/year, with a total project investment of RMB 56.2 billion.

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2013
General Office of the State Council
Opinions on Further Accelerating the Extraction and Utilization of Coalbed Methane and Coal Mine Gas

- Raise the central government subsidy for the development and utilization of coalbed methane and CMM.
- Allocate central government financial incentives to support closure of high-gas and small coal mines with coal and gas outbursts.
- Enhance tax and fee policy support, and improve coalbed methane pricing and power generation feed-in policy.

2016
Ministry of Finance
Notice on the Subsidy Standard for the Development and Utilization of Coalbed Methane and Coal Mine Gas during the 13th Five-Year Plan Period

- The central government subsidy for the exploitation and utilization of coalbed methane and CMM is increased from RMB 0.2/m^3 to RMB 0.3/m^3.

State Administration of Taxation
Notice on the Exemption of Import Taxes on Imported Materials for Coalbed Methane Exploration and Development Projects during the 13th Five-Year Plan Period

- For coalbed methane and CMM exploration and development projects within China, imported equipment, instruments, spare parts and special tools that cannot be produced domestically (or for which domestic performance does not meet the requirements) and are directly used for exploration and development shall be exempted from import tariffs and import-related value-added taxes.

2016
National Development and Reform Commission
Thirteenth Five-Year Plan for Development and Utilization of Coalbed Methane (Coal Mine Gas)

- By 2020, extract 14 bcm of underground drainage methane annually, and utilize at least 7 bcm — or 50%.
- Reach an installed CMM power generation capacity of 2.8 million kW, with use by more than 1.68 million households.
- Consolidate and develop a number of large-scale CMM extraction sites with annual volume of 100 million m^3.
- Encourage the safe, graded and at-scale utilization of CMM through civil use, CNG, LNG, concentration, power generation, and oxidation of ventilation air methane (VAM).

2019
Ministry of Ecology and Environment and others
Notice on Further Enhancing the Management of Environmental Impact Assessment on Coal Resources Development

- Gassy mines and mines with coal and gas outbursts should be equipped with facilities for methane drainage and utilization. For drainage methane with a methane volume concentration of≥8%, comprehensive utilization should be pursued, provided that safety is ensured.
- Encourage the exploration and comprehensive utilization of drainage methane with a methane volume concentration of 2%–8%, as well as VAM.

2023
Ministry of Ecology and Environment and others
Methane Emissions Control Action Plan

- By 2025, the annual utilization of underground drainage methane shall reach 6 bcm; the level utilization shall be further increased during the 15th Five-Year Plan period.
- Promote regular reporting of methane emissions data by coal mines.
- Accelerate the revision of applicable regulations and standards on coal mine safety.
- Further improve the methane emissions standard for coalbed methane (coal mine gas); developing stricter requirements for controlling methane emissions.
- Improve the trading mechanism for GHG resources and emissions reduction; supporting voluntary GHG emissions reduction trading for qualified methane utilization and emissions reduction projects.

2024
Ministry of Ecology and Environment
Revision of the Emission Standard of Coalbed Methane/Coal Mine Gas (Interim) (GB 21522-2008)

- Further reduce the concentration of controlled emissions: Emitting low-concentration CMM with a concentration ≥8% and a pure extraction volume ≥10 m^3/minute is prohibited.
- Construct CMM utilization facilities and provide other means of utilization, including power generation, for CMM that is prohibited from emission.
- Low-concentration drainage methane with a concentration less than 8% or a pure extraction volume less than 10 m^3/minute and VAM should be explored and comprehensively utilized, provided that safety is ensured.

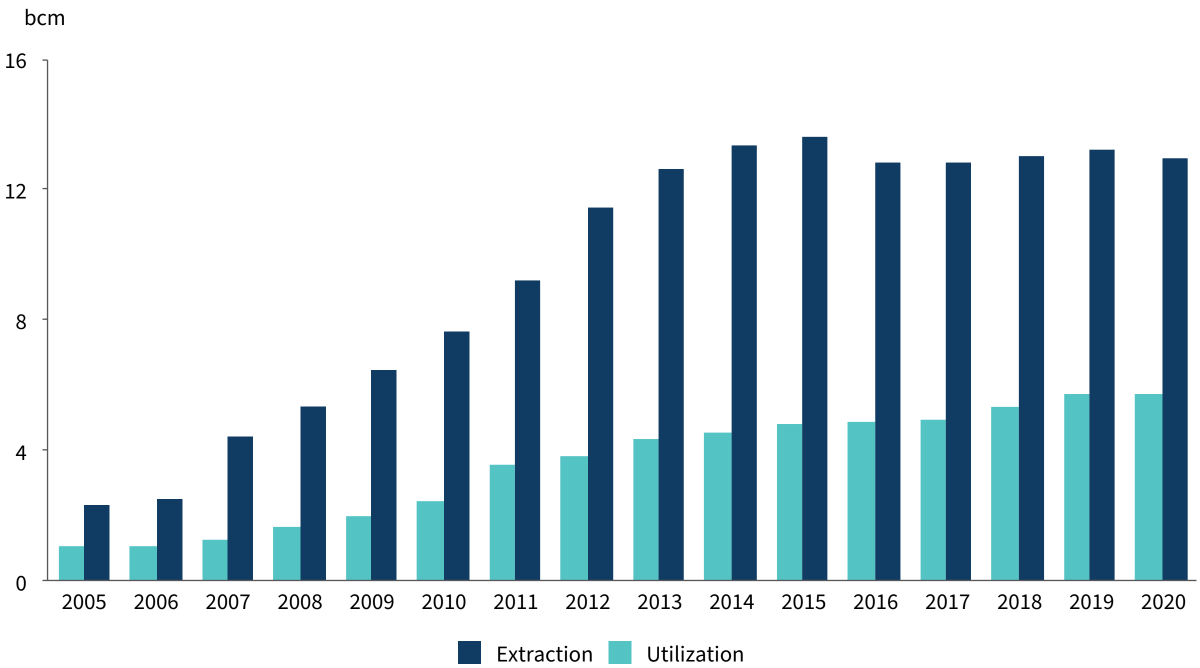
RMI Graphic.

Strategic planning | Supervision and management | Subsidies

China's Efforts in CMM Recovery and Utilization Have Begun to Show Results

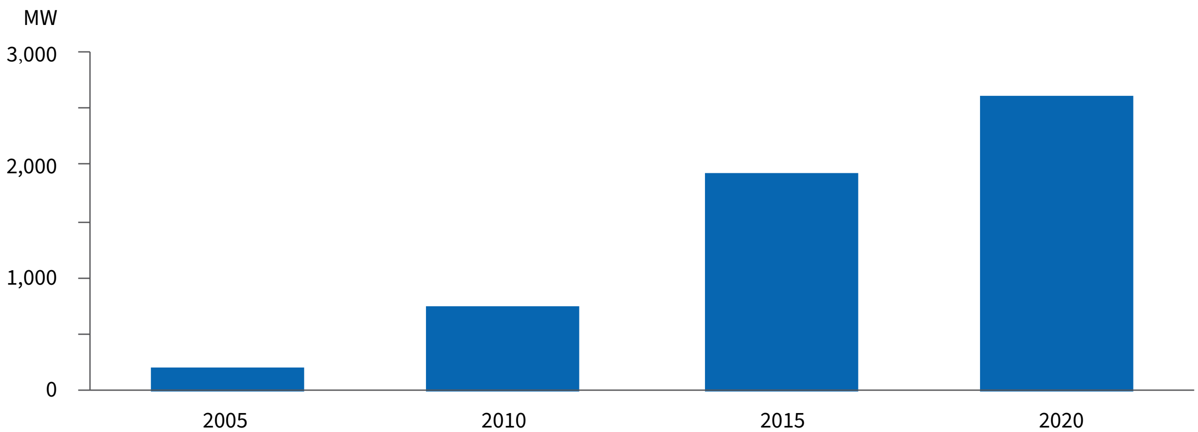
With the support of policy measures, the volume of methane drainage and utilization in Chinese coal mines has grown dramatically. In the past, coal mine enterprises often faced losses in methane utilization, with a common focus on methane drainage over utilization. In 2005, the underground drainage methane utilized in China was less than 1 billion m^3, the installed capacity of CMM power generation was about 200 MW, and the average utilization rate of drainage methane was about 30%.[9] With the support of various national and local policies, the CMM policy framework has steadily improved, investment in CMM resource exploration has increased, and the technological system for CMM recovery and utilization has become more sophisticated. As a result, more utilization projects have been completed and put into operation, leading to a rapid expansion of underground CMM recovery and utilization. By 2019, the underground drainage methane utilization volume reached 5.8 billion m^3, a 4.8-fold increase over 2005. The share of recovered and utilized methane in the coal industry's net methane emissions rose from 4% to 16% (as shown in Exhibits 8–10), effectively curbing the rapid growth of China's methane emissions.

Exhibit 8 **Underground methane drainage and utilization volume in China's coal industry**



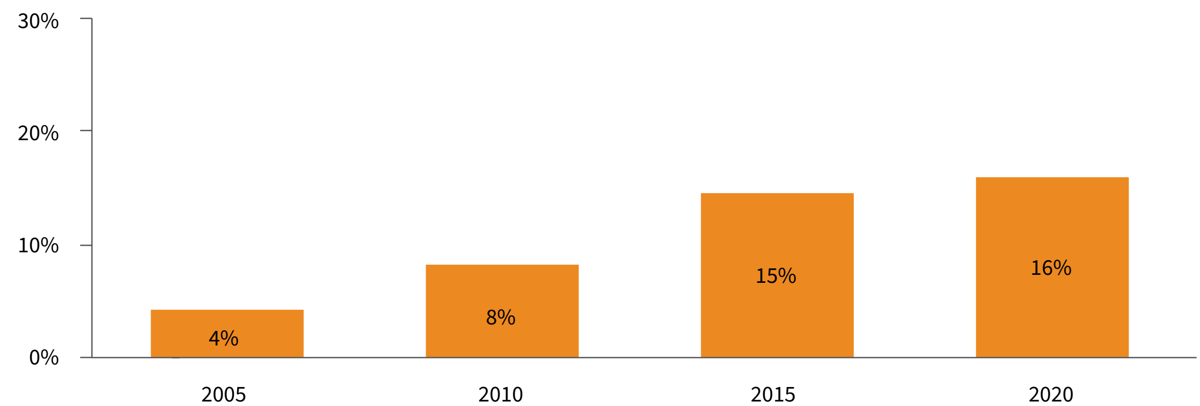
RMI Graphic. Source: Environmental Research Letters, **https://iopscience.iop.org/article/10.1088/1748-9326/ac38d8/meta**, Coal Processing and Comprehensive Utilization, 2018(8):59-61,66. DOI: 10.16200/j.cnki.11-2627/td.2018.08.013, and Coalfield Geology and Exploration, **http://www.mtdzykt.com/cn/article/id/75e1e45c-fe36-4a39-b0ef-36a58a9d4321**, and RMI analysis.

Exhibit 9 **Changes in installed capacity of CMM power generation in China**



RMI Graphic. Source: National Energy Administration

Exhibit 10 **The proportion of CMM utilization in the net methane emissions of China's coal industry**



RMI Graphic. Source: RMI Analysis

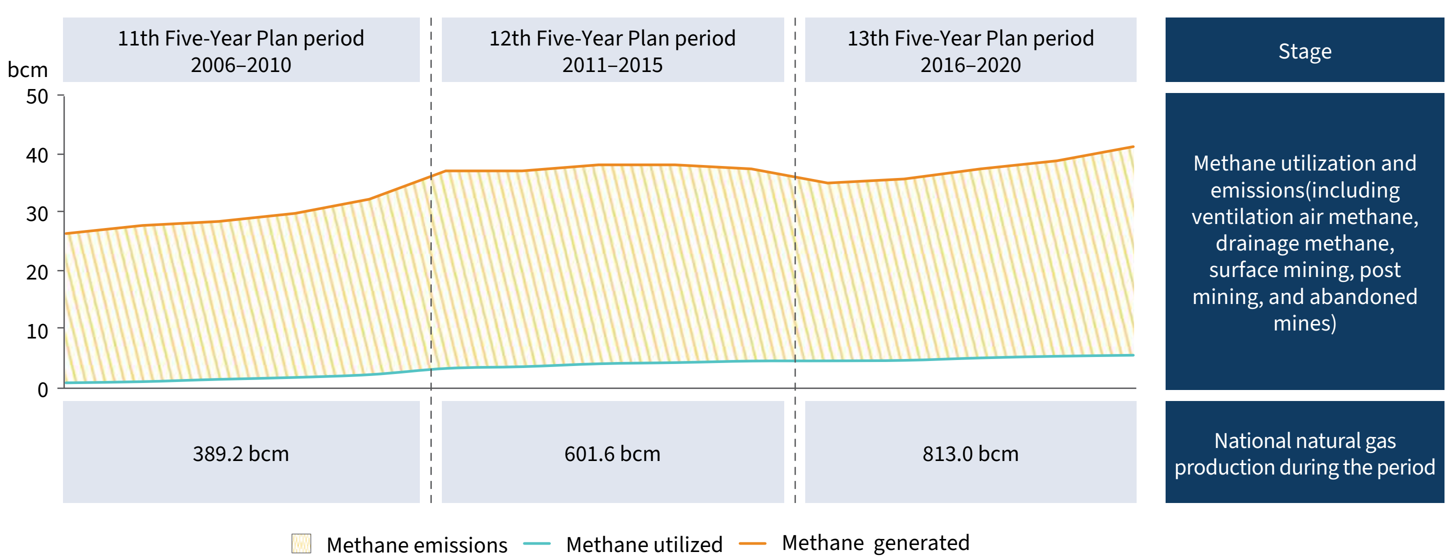
Development Potential and Technological Advancements

CMM Recovery and Utilization Has Ample Room for Improvement

CMM recovery and utilization contributes to increasing energy supply in China. The calorific value of CMM is 2–5 times higher than that of coal. Each cubic meter of purified CMM is equivalent to 9.5 kWh of electricity, 1.13 kg of gasoline, and 1.2 kg of standard coal.[10] China has a significant demand for natural gas and a high level of dependence on imports. In 2023, the nation's natural gas consumption reached 391.7 bcm, an increase of 6.6% over 2022. This includes an 8.2% increase in urban gas consumption, a 9.6% increase in gas for power generation, and a 6.1% increase in industrial gas consumption. Domestic gas accounts for only 58% of China's gas supply, while imported LNG and imported pipeline gas account for 25% and 17%, respectively.[11] Recovered CMM can be used as fuel and feedstock for residential use, power generation, and industrial applications. This resource helps reduce China's dependence on imported natural gas and bolsters energy security.

China has substantial CMM in its coal mines, indicating significant potential for recovery and utilization. Methane currently being recovered comes primarily from underground coal mines. According to RMI's estimates, the overall utilization rate of CMM is about 14% if considering the methane emitted from underground mines, open-pit coal mines, post-mining activities, and methane escaping from abandoned mines. In 2020, about 35.8 bcm of methane escaped from the coal sector, accounting for 19% of the country's natural gas production, 27% of the natural gas imports, and 11% of the natural gas consumption in the same year (see Exhibit 11). If China could increase the overall utilization rate of CMM to 30%, it would lead to an additional annual utilization of 6.6 bcm, which would correspond to a 5% reduction in that year's natural gas imports or savings of 8 million tons of standard coal.

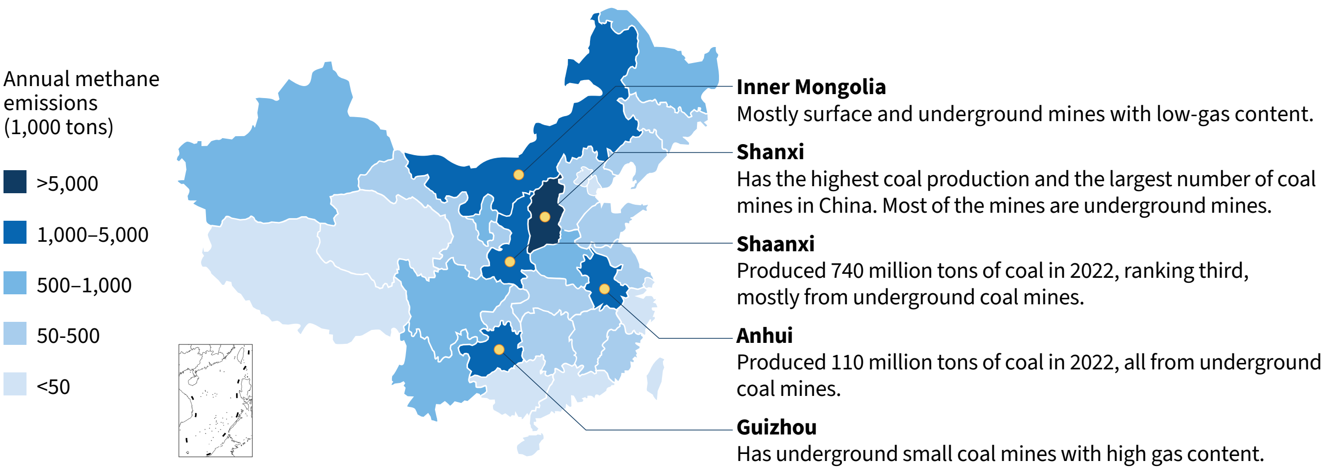
Exhibit 11 **Methane emissions and utilization in China's coal sector**



Note: "Methane generated" refers to the total amount of methane emitted into the atmosphere from coal production each year without considering CMM recovery and utilization; "methane emissions" refers to the annual net methane emissions from the coal industry.
RMI Graphic. Source: RMI analysis

The potential for increasing methane utilization mainly lies in VAM, low-concentration drainage methane, and abandoned mine methane. Shanxi Province produces the most coal in China, boasting many underground coal mines and abundant CMM resources (see Exhibit 12). The province has already achieved the industrialization of coalbed methane and coal mine gas, building two industrialization bases in Qinshui Basin and the eastern edge of Ordos. This has resulted in a comprehensive industrial system that includes exploration and development, equipment manufacturing, engineering services, and methane utilization. By 2018, more than 140 CMM power plants had been built in the province, with a total installed capacity of 1,600 MW. The utilization of CMM in the province accounted for approximately 50% of the national total. The primary utilization methods include power generation and residential use with power generation being the most significant use, accounting for 67.8%. Residential consumption made up 18.7%, and other means of consumption, such as boilers, accounted for 13.5%.[12]

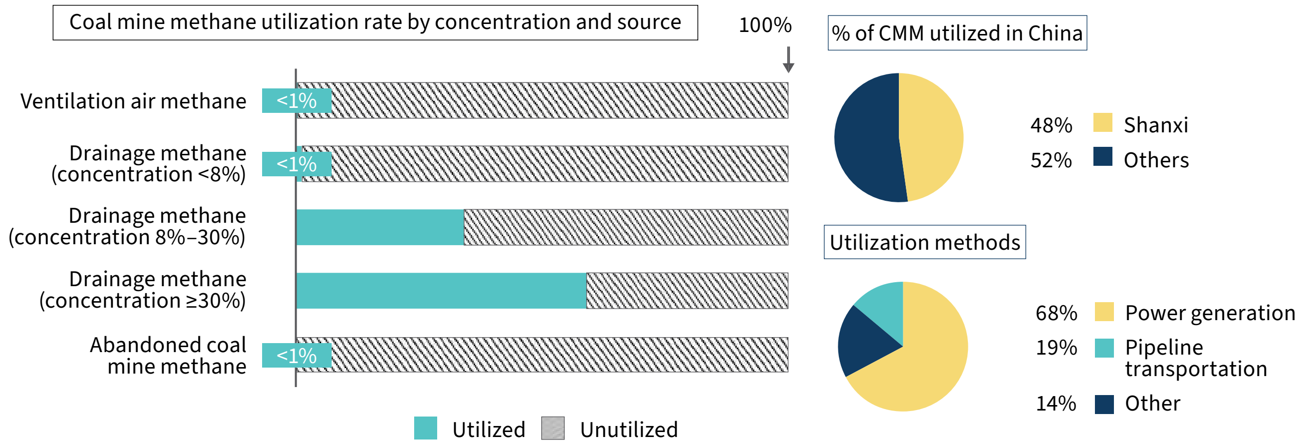
Exhibit 12 Methane emissions from coal mines by province in China (2022)



RMI Graphic. Source: RMI analysis

RMI estimated and analyzed the overall utilization of CMM in underground coal mines in Shanxi Province. There are significant disparities in utilization rates based on concentration and source: Most of the CMM recovered and utilized in Shanxi is drainage methane with a concentration above 8% and is primarily used for power generation, city gas, industrial fuel, and boiler fuel. However, the utilization rate for drainage methane with a concentration below 8%, VAM, and abandoned mine methane is less than 1% (see Exhibit 13). Thus, there is considerable potential for the recovery and utilization for CMM from these sources, making them key growth areas for the future.

Exhibit 13 Utilization of CMM in Shanxi Province



RMI Graphic. Source: Mining Safety & Environmental Protection, http://kyaqyhb.com/article/doi/10.19835/j.issn.1008-4495.2022.02.024?viewType=HTML

The Technological Readiness and Economics Feasibility of CMM Recovery and Utilization Should Be Improved

The reasons that CMM recovery and utilization's potential has not yet been fully unlocked are:

Uneven development of methane recovery and utilization technologies: The development of low-concentration drainage methane and VAM technologies remains in the demonstration stage, while technologies for abandoned mine methane are still in their infancy. In contrast, high-concentration drainage methane technologies are generally mature and have achieved commercial application. As a result, most CMM utilization projects currently focus solely on high-concentration methane. The maturity levels of various technologies, illustrated in Exhibit 14, are as follows:

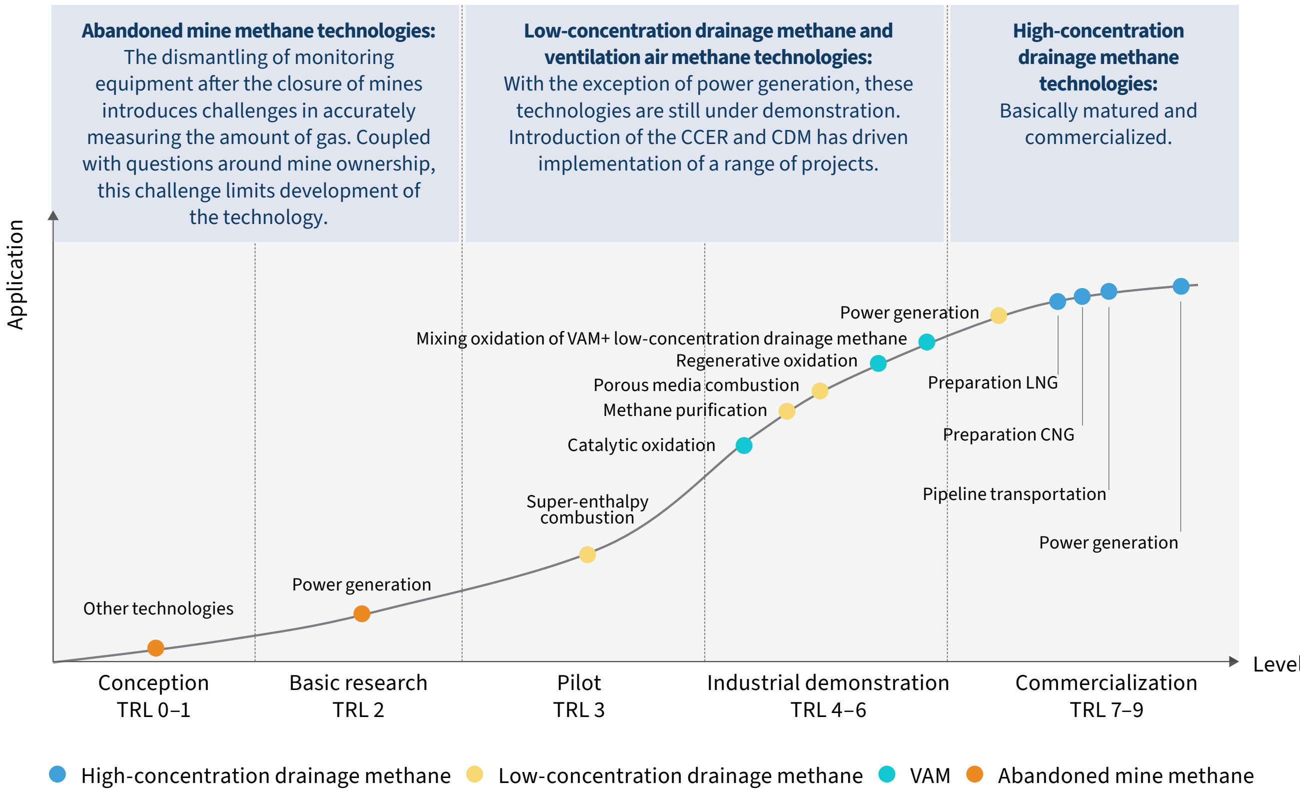
- **High-concentration drainage methane:** With high methane content and high calorific value, high-concentration drainage methane generates more energy during utilization, and is widely used in power generation, pipeline gas, purification, and other applications. The overall Technology Readiness Level (TRL) exceeds 7 and has reached level 9 for power generation, which is the most widely used CMM utilization technology.

- **Low-concentration drainage methane:** With methane concentrations of 5%–16%, this range is prone to explosions while also producing significant energy. Low-concentration methane power generation technology leverages this characteristic to convert chemical energy into electrical energy,[13] with a TRL of 7 to 9. Direct combustion heating technologies, such as porous medium combustion and super-enthalpy combustion, are suitable for concentrations of 4%–8%. These technologies have lower power density and have been developed more recently, currently existing in the pilot testing and industrial demonstration stages, with a TRL ranging from 3 to 5.

- **VAM:** The recovery and utilization technologies for VAM primarily focus on catalytic oxidation and regenerative oxidation. Driven by policies and market mechanisms such as China's Certified Emission Reductions (CCER) and the Clean Development Mechanism (CDM), a number of recovery and utilization projects were established during the 11th to 13th Five-Year Plan period (2006 to 2020). The TRL for these technologies ranges from 4 to 6.

- **Methane from abandoned mines:** R&D for methane recovery and utilization technologies for abandoned mines in China is still in the early stages. Shanxi Province has initiated efforts in areas such as Jincheng and Xishan, focusing on extracting methane from abandoned mine goaf areas. The TRL for abandoned mine methane utilization ranges from 1 to 3.

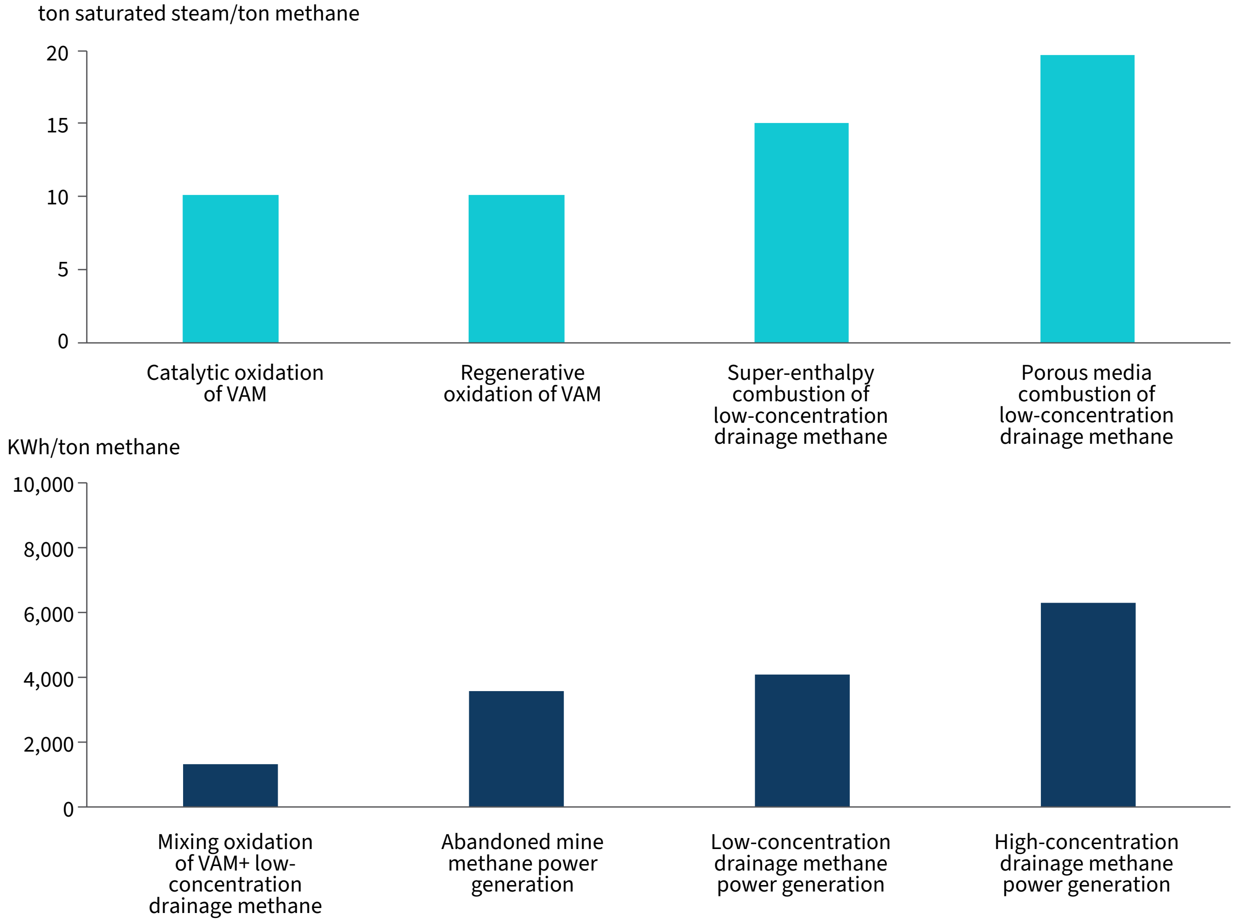
Exhibit 14 Maturity of CMM recovery and utilization technologies



RMI Graphic. Source: RMI analysis

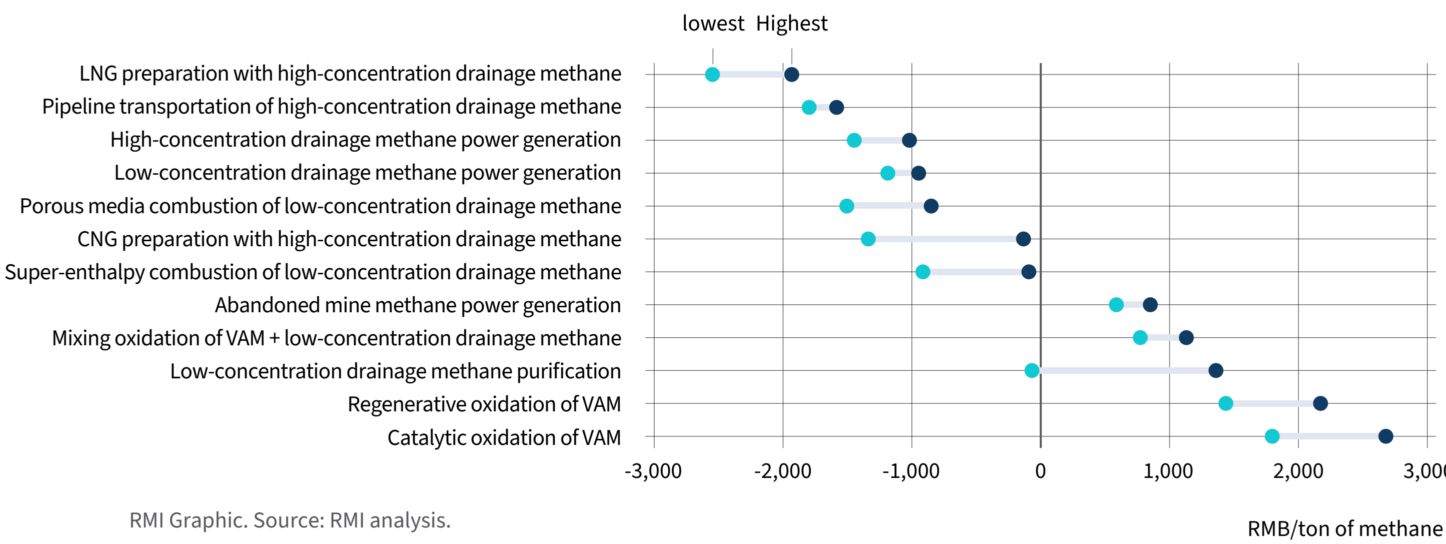
The economic viability of recovery and utilization technologies for low-concentration drainage methane, VAM, and abandoned mine methane is suboptimal. Due to differences in energy density arising from varying methane concentrations, low-concentration and VAM yield lower energy outputs after recovery, resulting in lower profits from electricity and heat sales (see Exhibit 15). Additionally, the utilization of low-concentration methane often requires more complex technologies, leading to higher construction and maintenance costs. Currently, the technological maturity and market acceptance of VAM utilization and low-concentration drainage methane direct combustion technologies are limited, which further restricts their application. The most economically viable technology is high-concentration drainage methane utilization, with net returns of RMB 100–RMB 2,500/ton of methane. Low-concentration drainage methane direct combustion technology has net returns of RMB 70–RMB 1,500/ ton. Meanwhile, the net cost for recovering VAM, abandoned mine methane, and purifying low-concentration drainage methane are up to RMB 2,700/ton of methane, making profitability a challenge without subsidies (see Exhibit 16).

Exhibit 15 Unit heat production and unit power generation of CMM recovery and utilization technologies



Note: In this report, the analysis of abandoned mine methane recovery and utilization technology involves only the extraction of high-concentration CMM from abandoned mines for power generation.
RMI Graphic. Source: RMI analysis.

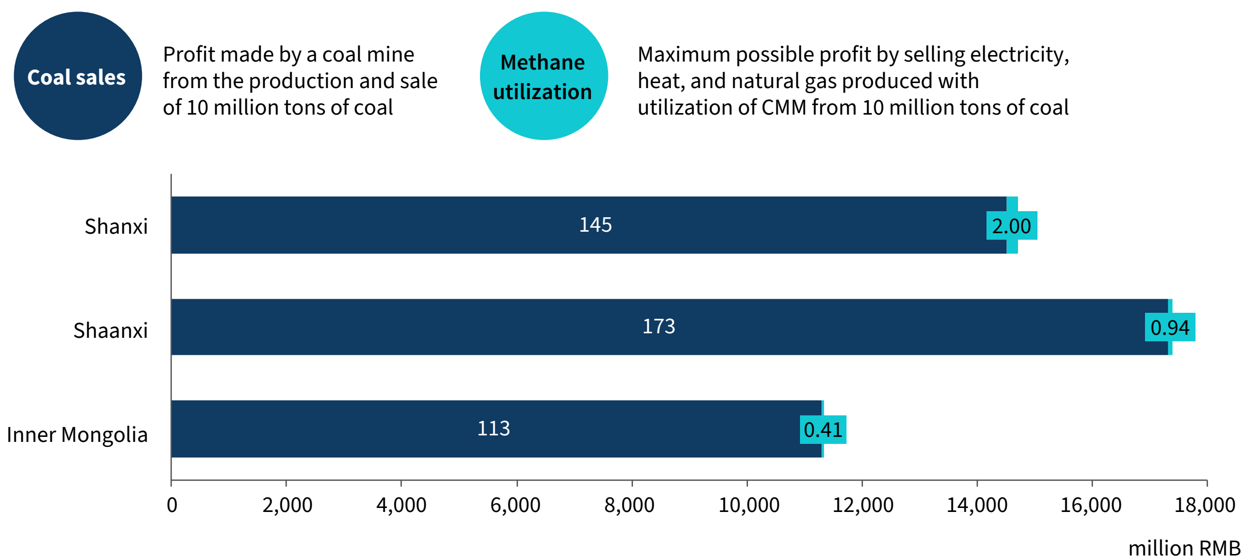
Exhibit 16 Cost of CMM recovery and utilization technologies (including revenue from sales of electricity, heat and gas, etc.)



RMI Graphic. Source: RMI analysis.

Compared to traditional energy production and sales, the profits from methane recovery and utilization projects are limited, making it challenging to motivate enterprises: When comparing the profits from coal production with those from methane utilization, a coal mine can earn RMB 113 million–RMB 173 million for every 10 million tons of coal produced and sold. Even in the case of a gassy coal mine that extracts high-concentration methane using economically viable technologies, the maximum profit from selling electricity, heat, and natural gas is likely to be less than RMB 2 million, accounting for just 0.3%–1.4% of the profit from coal production and sales (see Exhibit 17). Compared to coal sales, the revenue generated from methane recovery and utilization is very limited. Additionally, these projects require extra costs, technology investments, and human resources, all while balancing safety and supply security. As a result, enterprises are reluctant to invest in methane recovery and utilization projects, and the utilization volumes have not yet reached an ideal scale.

Exhibit 17 **Annual profits from coal sales vs. CMM recovery and utilization projects**



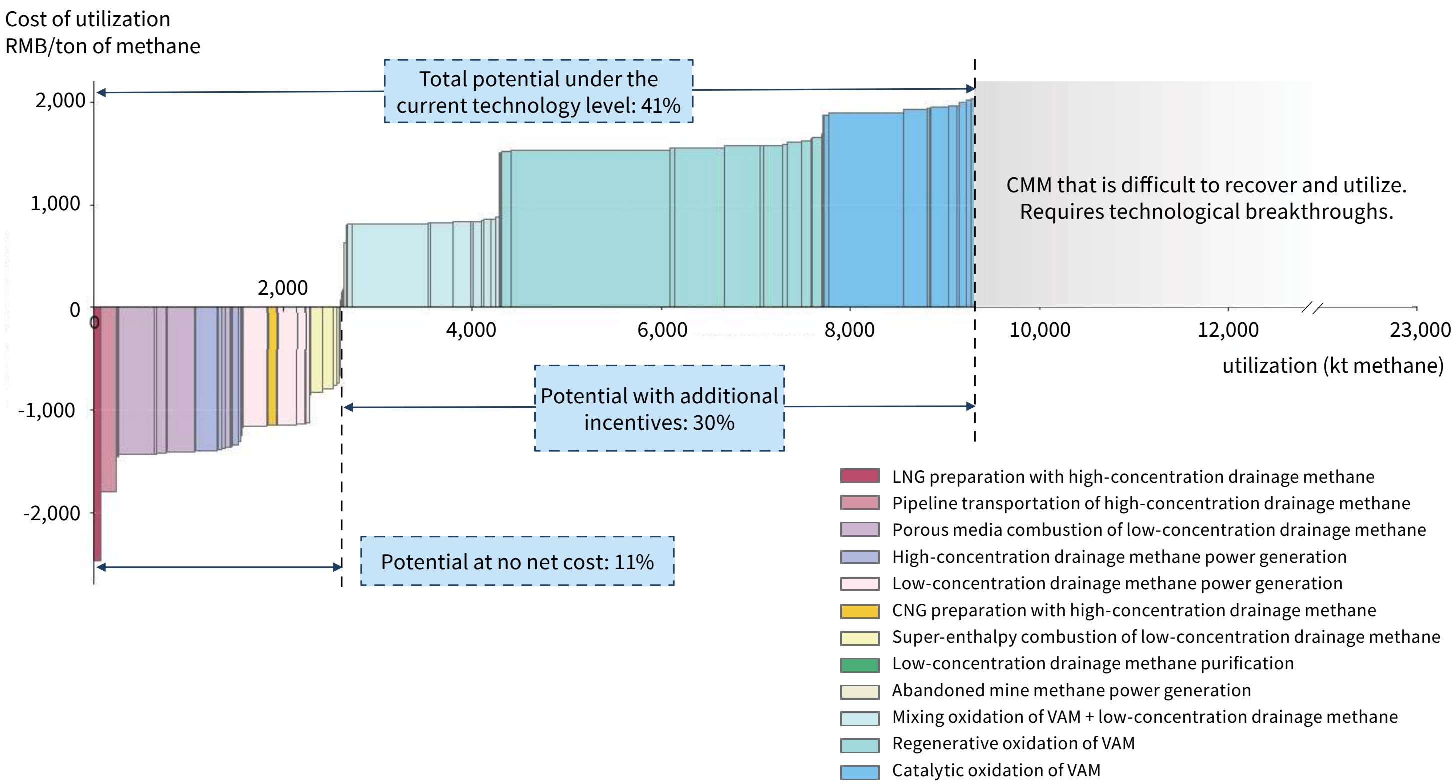
RMI Graphic. Source: RMI analysis

Instability of methane sources and ownership issues of abandoned mine methane: The concentration of methane emitted from coal production can fluctuate significantly, or the concentration may be high while the total volume remains low. To ensure stable operation during the implementation of methane utilization technologies, it is essential to have a relatively stable concentration and sufficient flow of methane gas. For instance, the capacity of individual units in methane utilization power plants in China generally ranges from 0.5 MW to 1 MW, while some imported generator sets can reach around 3 MW. Typically, a 3 MW methane utilization facility requires a minimum extraction rate of 9.9 m^3 per minute to operate effectively and manage methane processing. Coal mines may have trouble meeting the requirements for methane recovery and utilization technologies due to their geological conditions and physical constraints of the mine, making it temporarily unfeasible in some mining areas. Additionally, some methane recovery and utilization technologies must address ownership issues. For instance, the ownership of methane from abandoned mines in China is still unclear,[14] posing certain challenges for recovery and utilization efforts.

Potential and Cost-Benefit Analysis of CMM Recovery and Utilization Technologies

The technology for recovering and utilizing high-concentration drainage methane is profitable, and the potential for VAM utilization is significant. RMI has estimated the costs and benefits of various CMM utilization technologies in China. Considering factors such as technological efficiency, regional applicability, and implementation potential, we have developed a marginal cost curve for CMM utilization technologies (Exhibit 18). On this curve, the technologies are ranked from lowest to highest based on net utilization cost per ton of methane (in RMB, accounting for both costs and benefits). Currently, 41% of methane emissions can be utilized using existing technologies. Of this, 11% has the potential to be recovered at zero or negative net cost, while the remaining 30% will require additional investment and incentives.

Exhibit 18 **Marginal cost curve of CMM recovery and utilization technologies in China's coal industry**



RMI Graphic. Source: RMI analysis

Outlook for CMM Recovery and Utilization Technology

New Policies and New Markets Unlock New Opportunities for CMM Utilization Technology

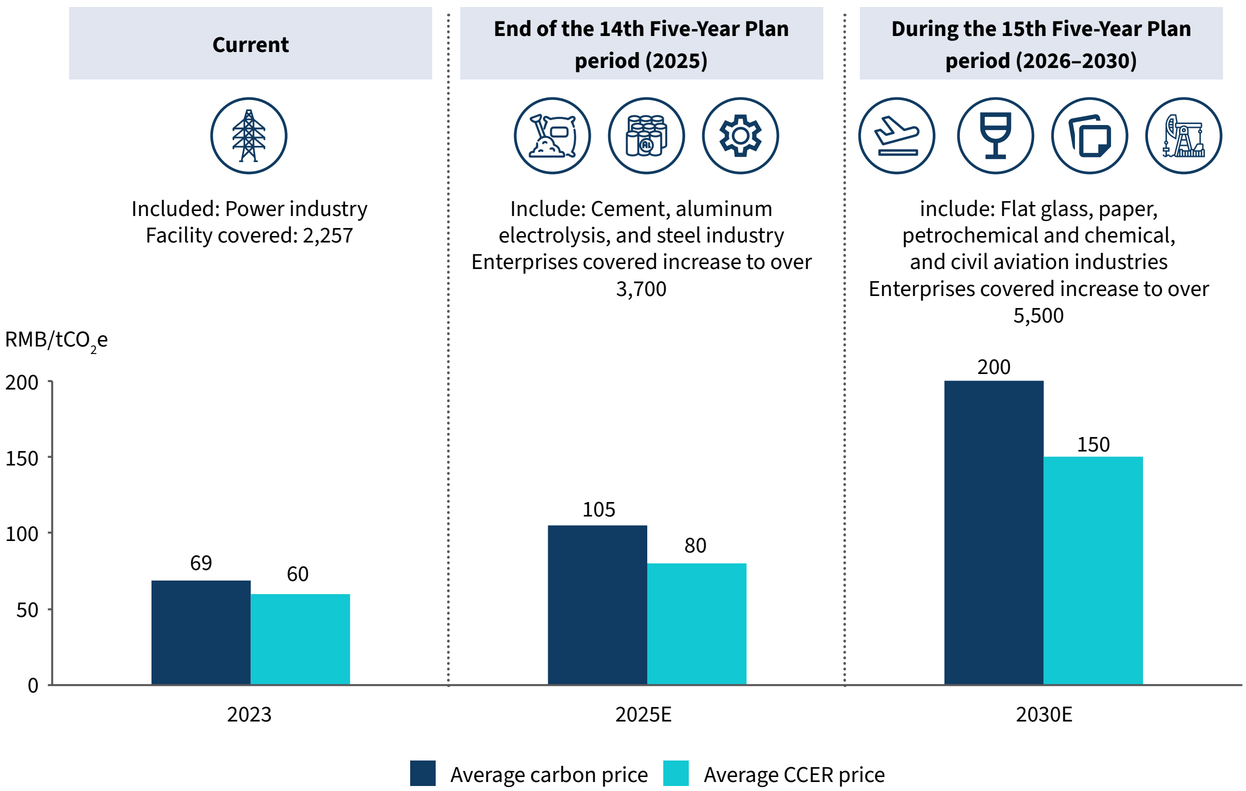
In recent years, China has been enhancing its CMM utilization policy. New national strategic objectives, standardization systems, and market mechanisms have been introduced and updated, unlocking new opportunities for CMM recovery and utilization technology:

On a strategic level, China's 2035 nationally determined contribution target is expected to enhance emissions control and accelerate CMM recovery and utilization. China's Methane Emissions Control Action Plan (NAP) proposes to encourage and guide coal enterprises to increase CMM recovery and utilization. It is one of the key efforts to promote the control of methane emissions in the energy sector. In 2023, China and the United States jointly released the Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis. China will develop methane reduction actions/targets for inclusion in its 2035 NDC and support methane reduction/control progress. The coal industry's initiatives in CMM recovery and utilization will play a key role in supporting the implementation of the NAP and the Sunnylands Statement, making a contribution to achieving China's climate strategy goals.

At a regulatory level, China has initiated the revision of methane emissions standards and coal mine safety regulations in the coal industry. The Ministry of Ecology and Environment has released a draft revision of the Emission Standard of Coalbed Methane/Coal Mine Gas for solicitation of opinions, which proposes to prohibit coal mines from emitting CMM with a concentration of greater than or equal to 8% and from extracting 10 m^3 or more pure methane per minute. This is an important update to the original 30% methane concentration emission limit, supporting construction of low-concentration CMM utilization facilities for coal mines and utilization of recovered CMM for power generation, heat supply, and other purposes. China is also accelerating the revision of coal mine safety regulations and standards. The Coal Mine Safety Regulations 2022 has been revised to partially lift the restrictions on the utilization of low-concentration methane, allowing for pipeline transportation and utilization of low-concentration drainage methane, but prohibiting burning it as fuel gas. China is still actively revising the safety regulations, which will further promote compliance of low-concentration CMM combustion projects.

At the market level, China's emissions trading system is maturing, with a rising carbon price, improving profitability for methane utilization projects. China's carbon emissions trading market launched online trading in 2021 and has now become the world's largest GHG emissions market, covering 2,257 key emitters and about 5.1 billion tons of carbon dioxide emissions. This accounts for over 40% of the total carbon dioxide emissions in China.[15] China launched its voluntary GHG emissions reduction trading market in January 2024. It is now soliciting opinions on the methodology of voluntary emissions reduction projects for the utilization of low-concentration drainage methane and VAM in the coal mines.[16] Low-concentration drainage methane and VAM projects are expected to be included in the CCER market. Based on a 5% offset ratio, the coverage of the CCER market can reach 250 million tons of CO_2e, and with the expansion of the carbon market, it is expected to exceed 500 million tons of CO_2e. The continuous rise in carbon trading prices will also drive up CCER trading prices. According to expert predictions, the average CCER transaction price is expected to reach RMB 150/t CO_2e by 2030 (see Exhibit 19). The climate value generated by CMM recovery and utilization in the coal industry is likely to be reflected in the CCER market, significantly improving the economic viability of such projects and motivating enterprises to pursue methane utilization.

Exhibit 19 Carbon market and carbon price trend predictions in China



RMI Graphic. Source: Journal of Beijing Institute of Technology, **http://journal.bit.edu.cn/sk/article/doi/10.15918/j.jbitss1009-3370.2024.7182**, and Ministry of Ecology and Environment, **https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202409/t20240909_1085452.html**

By evaluating across three dimensions — technology maturity, economic feasibility, and emissions reduction potential — CMM recovery and utilization technologies can fall into four main categories: mature, growth, cost-efficient, and exploratory (see Exhibit 20). With policy guidance and market forces, each category of technology has different development potential:

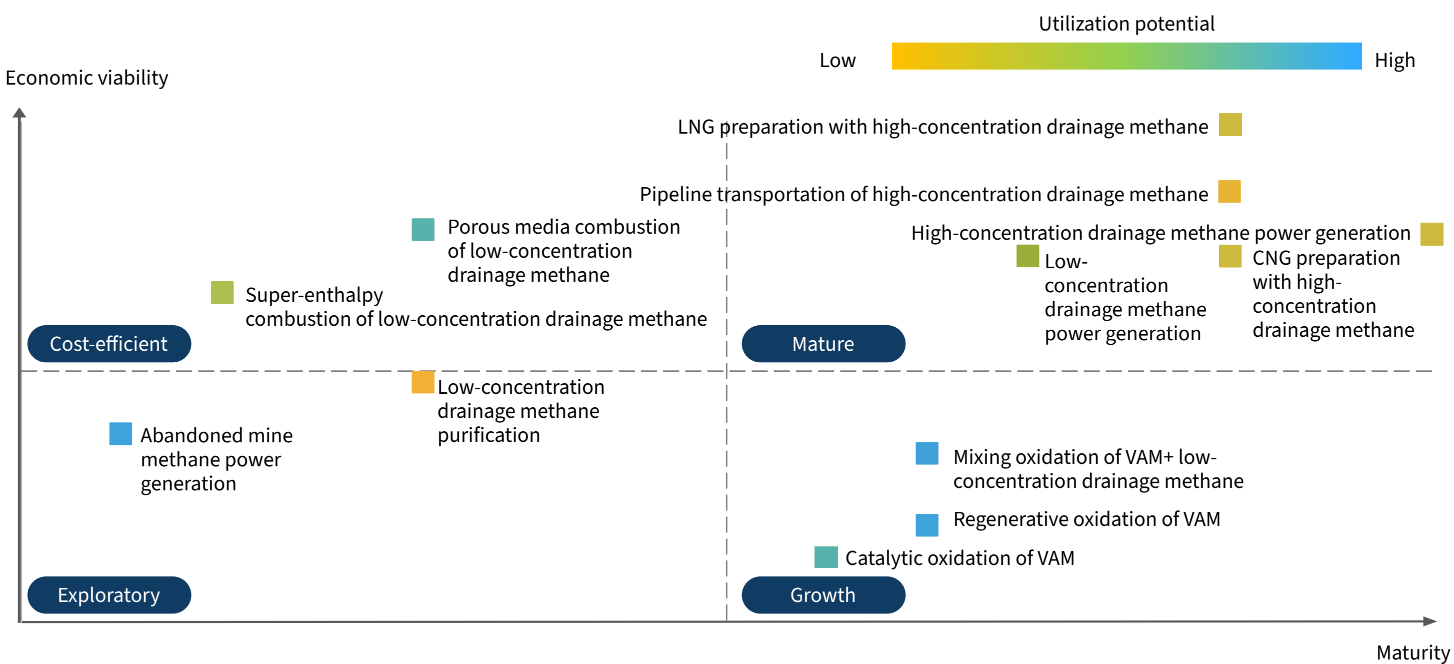
- **Mature technology:** These technologies are highly mature and economically viable, with commercial applications already in place. They are the leaders and mainstream in China's CMM recovery and utilization technologies. The main mature technologies include high-concentration drainage methane utilization and low-concentration drainage methane power generation. High-concentration methane holds significant energy value, and due to policy incentives, it has been nearly fully utilized. As a result, there is limited room for developing new projects at existing coal mines. In the future, the development opportunities for high-concentration technologies will primarily focus on newly built mines with high gas levels, where the appropriate utilization methods will depend on factors such as geographical location and resource conditions.

- **Cost-efficient technology:** Cost-efficient technologies offer good economic viability and can generate considerable returns once projects are completed. They also possess a certain degree of recovery and utilization potential, with a focus on the development of relatively new technologies such as porous medium combustion and super-enthalpy combustion technologies. The advancement of cost-efficient technologies requires priority attention to market acceptance and compliance issues. Because the applicable methane concentration for these technologies is generally below 8%, they are not subject to existing mandatory regulatory policies. Additionally, the acceptance of direct combustion methods that involve flames is relatively low in coal enterprises, which may pose compliance risks. However, as policies and regulations are revised and implemented, coal producers' acceptance of these technologies is expected to increase. With their cost-effectiveness and significant emissions reduction potential, they are likely to experience favorable development.

- **Growth technology:** This category is primarily focused on VAM utilization technology, which is typically in the industrial demonstration phase and has a certain scale supported by policies. The main challenge facing growth technologies is their economic viability. Growth technologies can achieve higher overall income by securing subsidies and premiums through market mechanisms, thereby expanding their application range. In China, underground coal mines are equipped with ventilation air systems, and although there are over 1,800 gassy and gas-outburst mines,[17] only around 20 ventilation air methane utilization projects are established and currently operational. The development of market mechanisms is expected to promote growth technologies in the future.

- **Exploratory technology:** This category of technologies has limited maturity and economic viability, encompassing abandoned mine methane recovery technologies and low-concentration methane purification technologies. At this stage, exploratory technologies require targeted research and development to achieve breakthroughs. For instance, in the case of abandoned mine methane recovery technologies, as the number of abandoned mines in China increases in the future, the demand for emissions control and resource utilization from these abandoned mines will continue to rise. Sufficient investment in R&D, along with practical engineering applications, will lay a foundation for the successful implementation of these projects.

Exhibit 20 **Development matrix of CMM recovery and utilization technologies**



RMI Graphic. Source: RMI analysis

Growing Maturity and Decreasing Cost of CMM Recovery and Utilization Technology

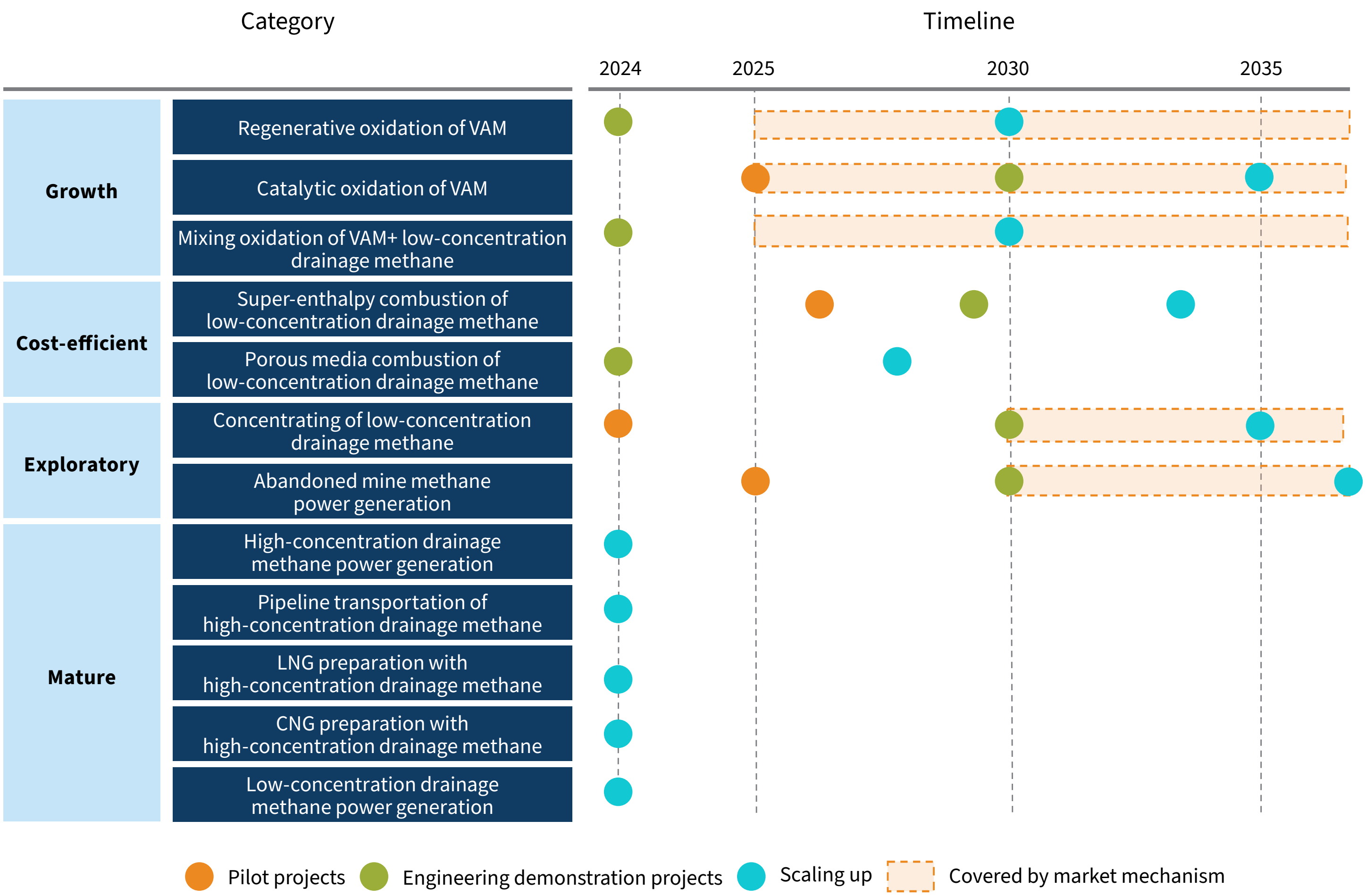
RMI analyzed and projected the development of CMM recovery and utilization technology in China up to 2035. Under the technically feasible scenario, CMM recovery and utilization in the coal industry will shift from a landscape dominated by high-concentration methane technology to “comprehensive utilization of CMM with graded concentration” in the next decade (see Exhibit 21). Unlocking the full potential of CMM recovery and utilization will entail key developments, including:

- **2025–2027: The market mechanism will gain initial results.** During this period, mature technology will stabilize, and utilization projects continue to focus on power generation from high- and low-concentration methane. Growth technology will rapidly grow under the market mechanism. The methodology of voluntary emissions reduction in methane utilization projects will be optimized. The first batch of newly built VAM utilization projects will be launched and participate in CCER trading, with the scale of VAM utilization, and emissions reduction transactions beginning to take shape. Meanwhile, investment in exploratory and cost-efficient technologies will increase over time to accelerate the R&D of VAM catalysts and process optimization. Comprehensive utilization of abandoned mine resources will be explored, and laboratory demonstration and pilot studies will be performed on the utilization of abandoned mine methane, purification of low-concentration methane, and super-enthalpy combustion.

- **2027–2030:** Technological breakthroughs and pilot implementations will be completed during this period. The application range of growth technologies will further expand, with the development of catalysts for VAM catalytic oxidation technologies reaching maturity and entering practical use. The number of projects utilizing VAM thermal oxidation technologies will increase further, driven by market mechanisms, gradually achieving scalability. The revision and implementation of standards systems and safety regulations will be completed, leading to a gradual increase in market acceptance of efficiency technologies. Porous media combustion technology will be promoted in coal mining areas, and several engineering demonstration projects for super-enthalpy combustion will be established. Research and development efforts for exploratory technologies will continue, with pilot projects for abandoned mine methane power generation established. Feasibility analyses and the design of standards systems for incorporating exploratory technologies into the CCER market will also be conducted.

- **2030–2035:** The coverage of market mechanisms will be enhanced, leading to diversified utilization of CMM. With the expansion of the carbon market, the scale of the CCER market will increase, providing more opportunities for participation in methane mitigation projects. Growth technologies will achieve scalable development under the influence of market mechanisms. Exploratory technologies will gradually mature, with a number of demonstration projects for abandoned mine methane recovery and low-concentration drainage methane purification technologies established and operating stably. Related standards and methodologies for emissions reduction projects will also be progressively refined. The expansion of the CCER market will facilitate the scaling up of low-concentration CMM purification technologies by 2035 and abandoned mine methane technologies will achieve scalability before 2040.

Exhibit 21 **The outlook for CMM recovery and utilization technology maturity**

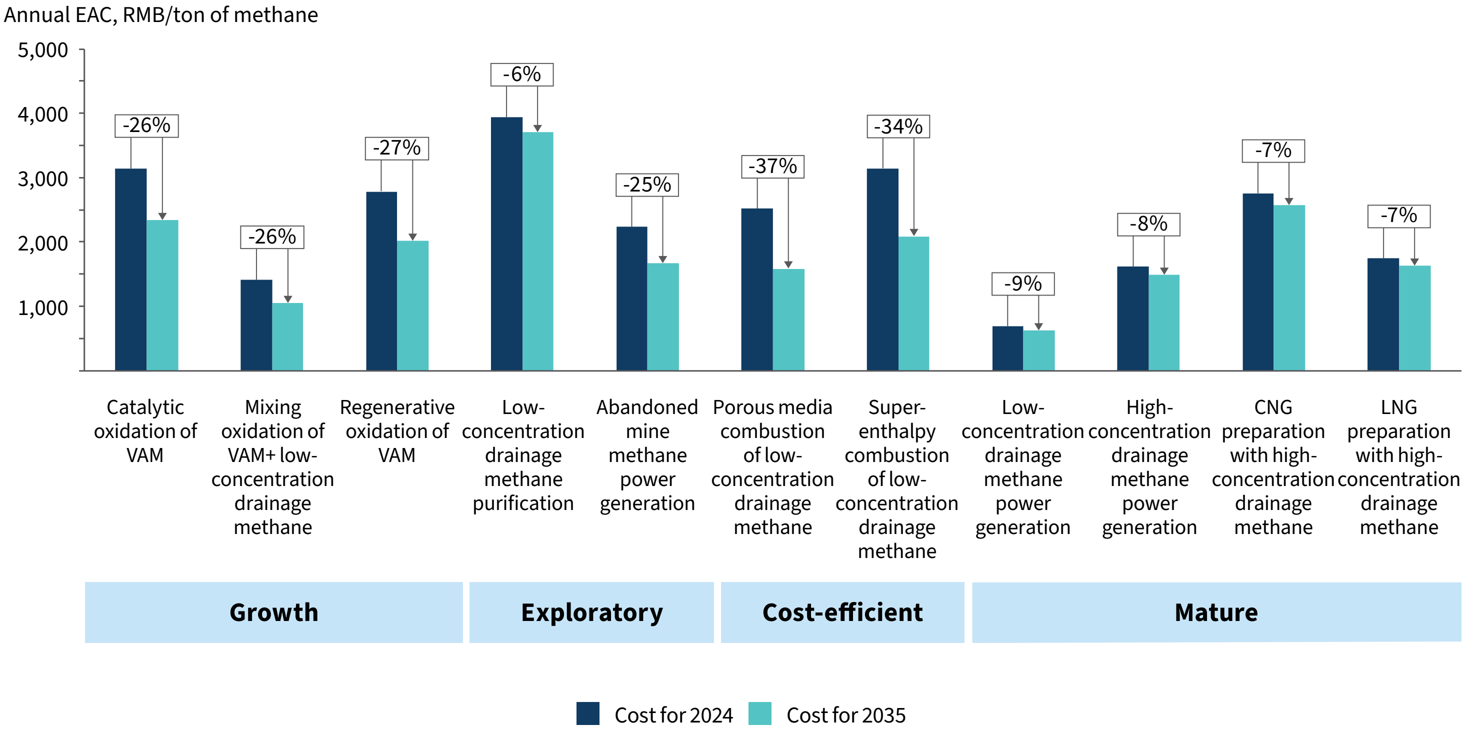


RMI Graphic. Source: RMI analysis.

As technologies evolve and are adopted, the economics of scale become more evident and the average annual cost of the technologies will decrease. RMI leverages the learning efficiency curve model to analyze the impact of technological progress and economies of scale on the average cost. Assuming that CMM recovery and utilization is implemented under the technically feasible scenario, the unit cost will decrease at a learning rate of 0%–10% as the overall utilization volume and methane emissions reduction increase. Taking 2024 as the base year, this report sets different learning rates for each technology and predicts changes of average cost in the future. By doing so, we conclude that the equivalent annual cost (EAC) of each category of CMM recovery and utilization technology may decline 6%–37% by 2035 (see Exhibit 22).

Among them, cost-efficient technology (low-concentration drainage methane super-enthalpy combustion and porous media combustion) shows the greatest potential for cost reduction — with a possible decrease in EAC of more than 30% by 2035 compared to the 2024 level. The cost of VAM utilization and abandoned mine methane utilization may decline 25%–27%, while the remaining may drop 6%–10% for higher levels of maturity or limited utilization volume. Without considering subsidies, carbon market benefits, and product sales revenue, if coal enterprises view methane recovery and utilization purely as a greenhouse gas emissions reduction measure, low-concentration drainage methane recovery technologies and VAM mixing oxidation technologies offer a relatively high cost-effectiveness ratio.

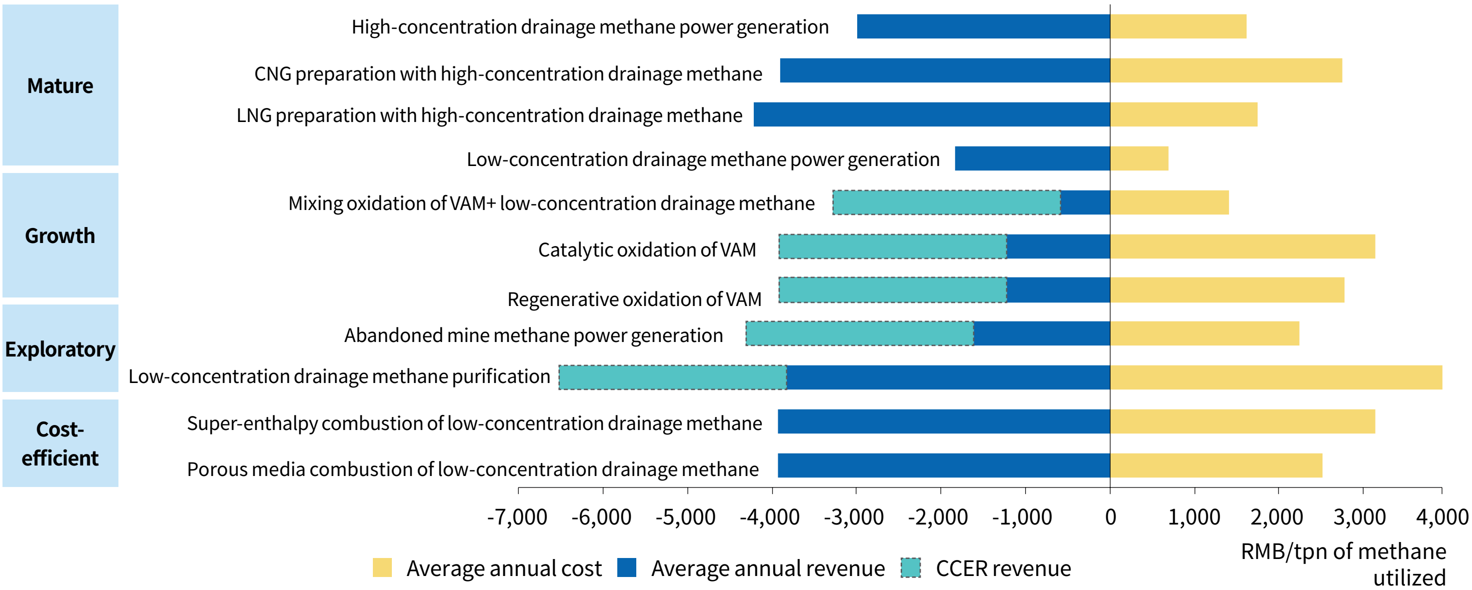
Exhibit 22 Equivalent Annual Cost (EAC) of CMM recovery and utilization technologies (excluding project revenue)



Note: The equivalent annual cost (EAC) accounts for both the capital costs of the project (including expenses for equipment, civil construction, installation, instrumentation, and safety measures) and the operating costs (including personnel salaries, fuel costs, repair costs, water fees, and material costs).
RMI Graphic. Source: RMI analysis.

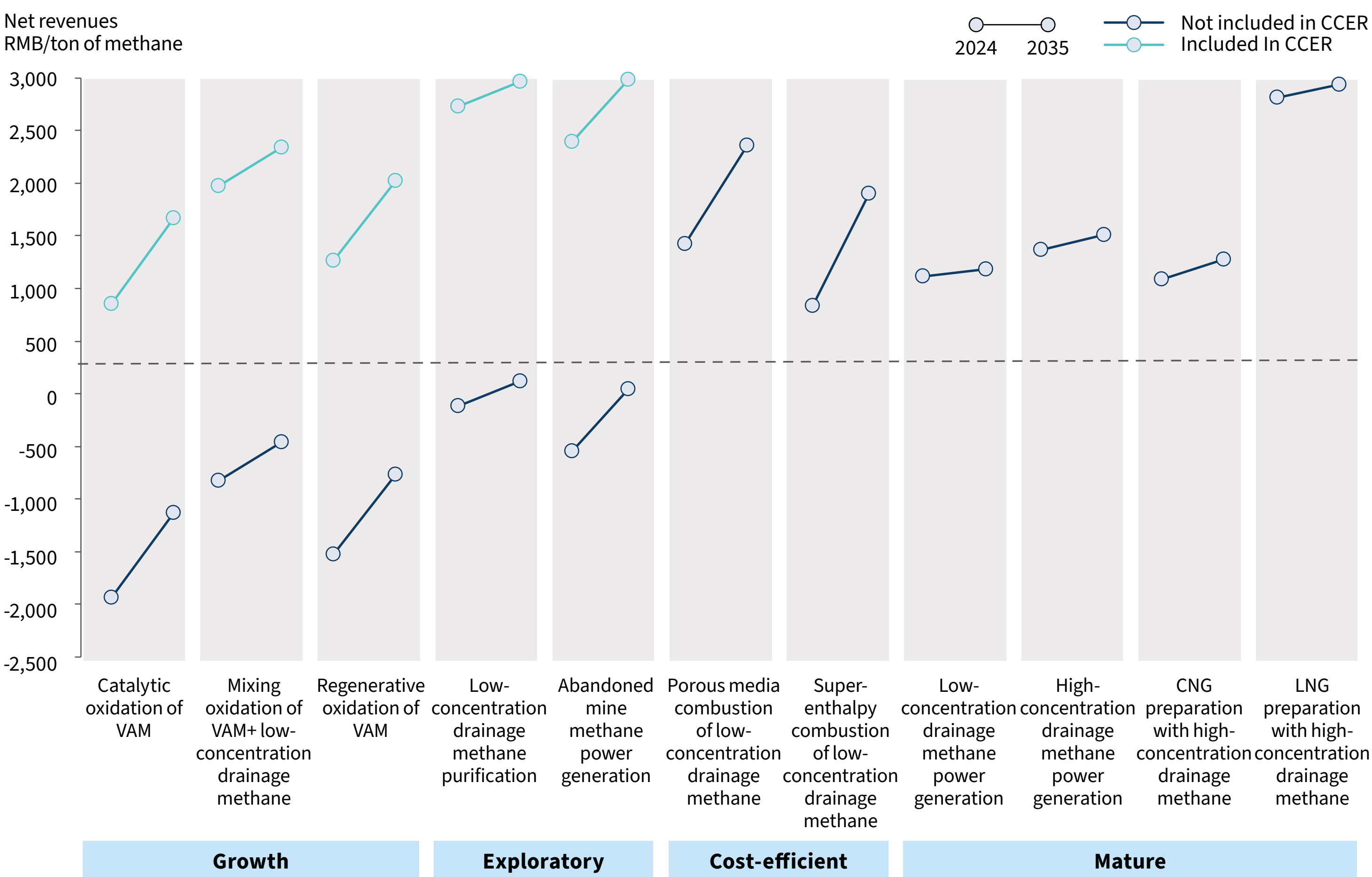
Considering energy sales and CCER returns, the economics of key technologies are significantly improved. For every ton of (pure) CMM recycled, mature and cost-efficient technologies generate RMB 1,800–4,000 in energy sales, and growth and exploratory technologies generate RMB 600–1,600 (see Exhibit 23). If capital and operating costs as well as revenues from energy sales are also considered, cost-efficient technologies can increase profits by more than 65% by 2035, offering the same economics as mature (see Exhibit 24). Even without CCER, growth and exploratory technologies can also significantly reduce net costs to RMB 115–RMB 1,100/ton of methane by 2035. If growth and exploratory technologies are included in CCER, project revenue can increase by two to five times (see Exhibit 25). CCER will enable these technologies to turn around and facilitate their adoption in the coal industry.

Exhibit 23 Average cost and revenue by technology in 2024



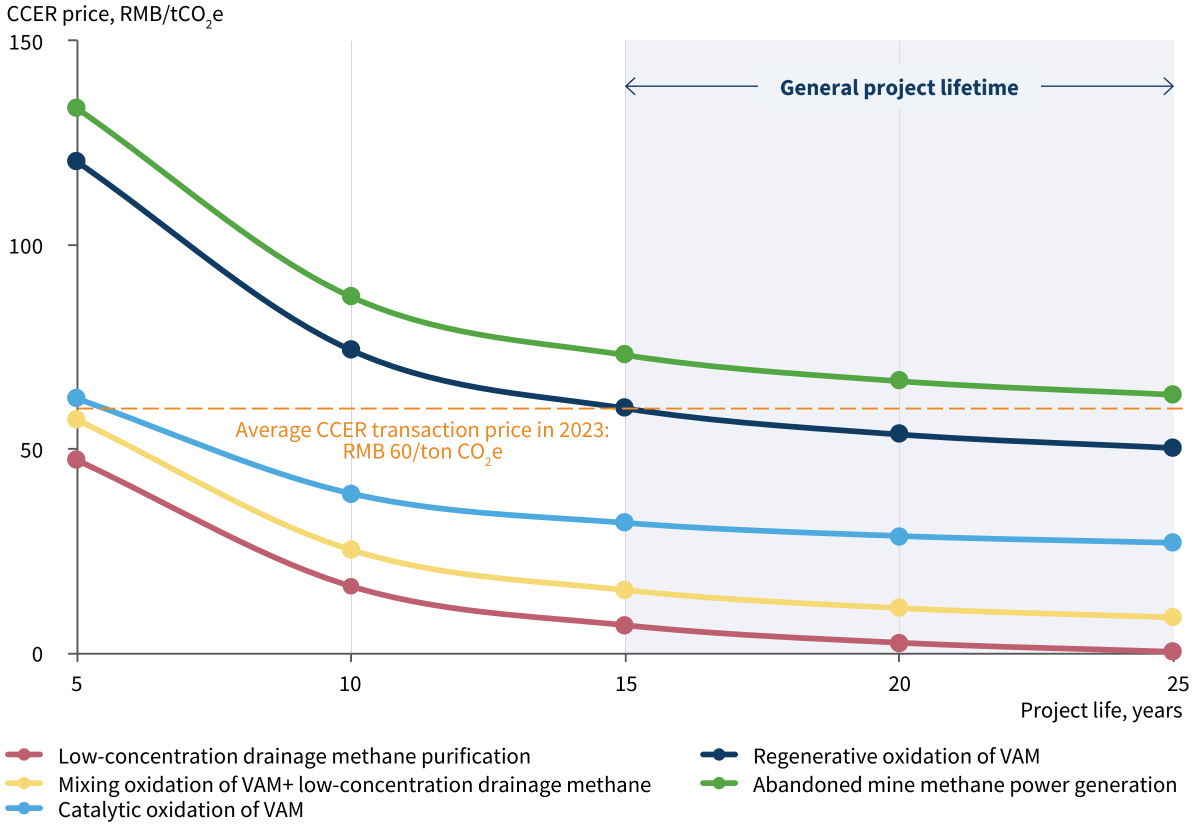
RMI Graphic. RMI analysis

Exhibit 24 Trend of net revenues from CMM recovery and utilization technologies



RMI Graphic. Source: RMI analysis

Exhibit 25 Zero-cost curve of CMM recovery and utilization technologies under CCER

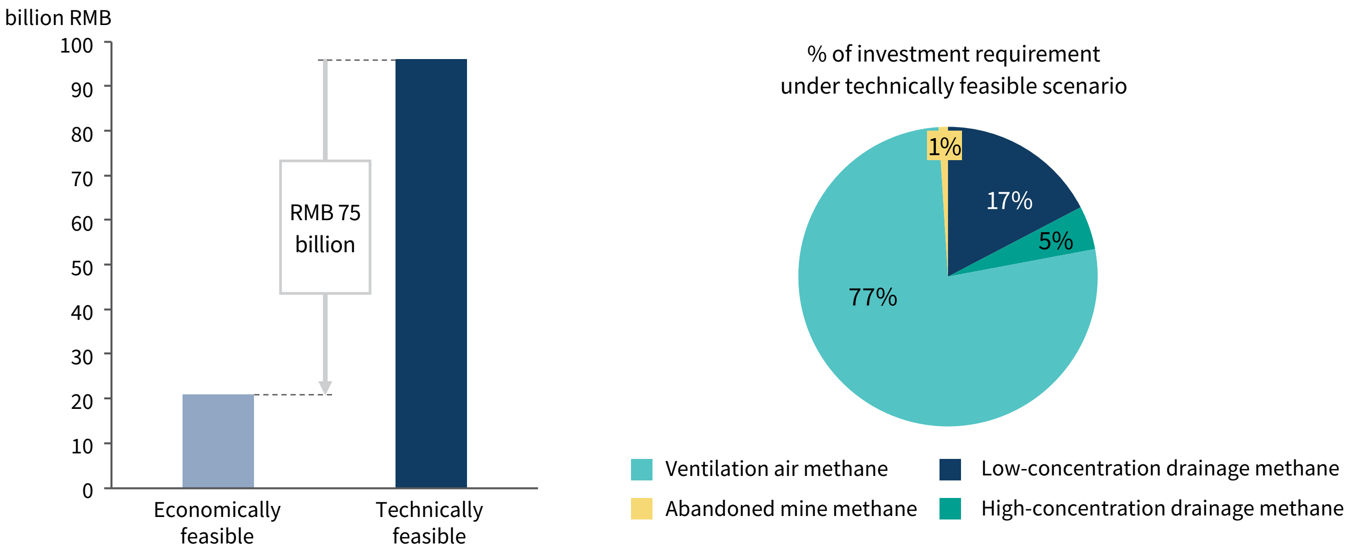


RMI Graphic. Source: RMI analysis

Investment Required and Market Size of CMM Recovery and Utilization Technologies

In a technically feasible scenario, an additional investment of 100 billion RMB is needed to support CMM recovery and utilization. CMM recovery and utilization is one of the key technologies for carbon reduction and resource recovery in coal production. Under the goal of carbon neutrality, as the upstream decarbonization willingness in the energy sector continues to rise, CMM recovery and utilization, as an economically viable emission reduction technology, will have significant development potential. According to RMI's calculations, if only economically feasible technologies are implemented (with utilization projects not participating in the CCER), the additional investment demand for CMM recovery and utilization is approximately 21 billion RMB. If all technically feasible utilization is considered, an additional 75 billion RMB in investment support will be required, bringing the total demand to nearly 100 billion RMB, primarily for the construction of VAM and low-concentration drainage methane utilization projects (see Exhibit 26).

Exhibit 26 **Investment demand for CMM recovery and utilization technologies**



RMI Graphic. Source: RMI analysis

CMM recovery and utilization generates an economic return of RMB 32 billion per year. RMI has estimated the annual market sales scale of various technologies' end products. In a technically feasible scenario, CMM recovery and utilization could generate approximately 15 billion RMB in energy sales revenue annually, with the sale of saturated steam being the primary revenue source, accounting for over 70% of energy sales revenue, while the remainder comes from electricity generation and gas sales (as shown in Exhibit 27). Additionally, CMM recovery and utilization can obtain green benefits of 17.5 billion RMB per year through the CCER market. For high-cost technologies, the market mechanism is crucial for project profitability, as CCER income contributes to over 40% of the total revenue from these technologies (see Exhibit 28).

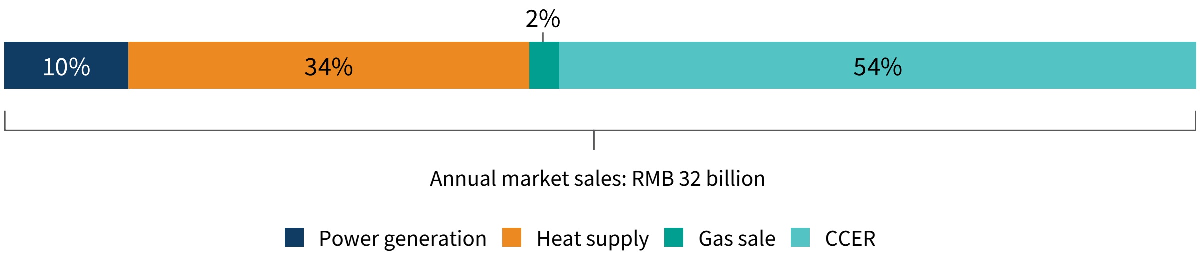
Social benefits of CMM recovery and utilization: Under the technically feasible scenario, CMM recovery and utilization can deliver the following values in addition to the direct economic benefits:

- **Energy supply:** CMM recovery and utilization projects can supply approximately 5.4 bcm of natural gas annually, accounting for about 2.4% of China's natural gas production in 2023. Additionally, gas power generation projects can produce 7.4 billion kWh of electricity each year, which is sufficient to meet 20% of the electricity needs of urban and rural residents in Beijing. Furthermore, the supply of saturated steam can be increased by 75 million tons annually, which, when calculated based on the replacement of coal-fired boilers, corresponds to an annual savings of 10 million tons of standard coal.

- **Employment:** CMM recovery and utilization projects require personnel in the construction, operation, and maintenance of the projects, which will create employment in the surrounding areas. RMI estimates that CMM recovery and utilization projects will create about 8,400 jobs and annual incomes of RMB 100 million.

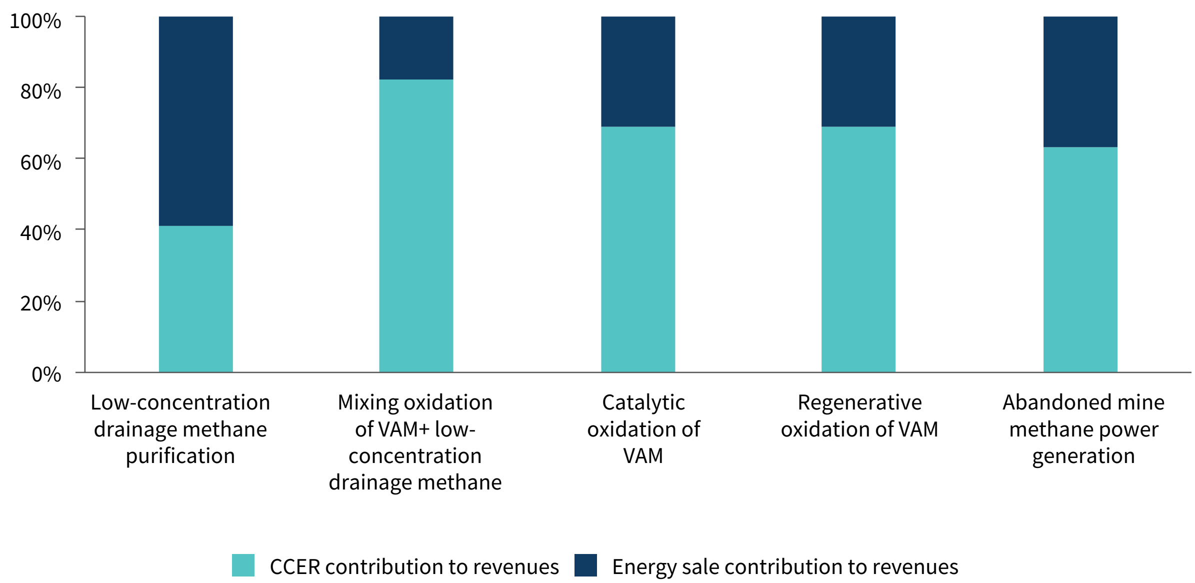
- **Emissions reduction:** CMM recovery and utilization can reduce methane emissions in the energy sector. Under the technically feasible scenario, implementing CMM recovery and utilization technology can reduce 250 million tons of CO_2e per year. This is equivalent to a 28% reduction in emissions from the transportation sector, 15% from the steel sector, and 5.5% from the power sector. Meanwhile, a decrease in fugitive emissions also generates health benefits worth an estimated RMB 20 billion and avoids RMB 1.6 billion in economic losses due to reduced food production.

Exhibit 27 Annual market sales of end products with CMM utilization technologies



RMI Graphic. Source: RMI analysis

Exhibit 28 CCER contribution to revenues from high-cost CMM utilization technologies



RMI Graphic. Source: RMI analysis

Recommendations

CMM recovery and utilization is one of the most important ways to reduce emissions from coal production, delivering benefits for climate, energy, health, and more. The Methane Emissions Control Action Plan and the establishment of the voluntary emissions reduction market have brought new opportunities and momentum for the CMM market. Coal companies should leverage their position at the upstream of the industry chain, and pass on the carbon emissions reduction benefits of CMM recovery and utilization to downstream coal consumers. This will facilitate a low-carbon transition across the entire supply chain, making a substantial contribution to China's climate goals. To accelerate the adoption of CMM recovery and utilization technologies, we propose the following actions:

Continue to enhance policy support and build a favorable market environment. Since the 11th Five-Year Plan (2006), China has made significant progress in underground drainage methane recovery and utilization through strategic planning, subsidies, and regulatory policies. Given this progress, further efforts are needed to accelerate the development and revision of relevant standards and regulations, including requiring the recovery of methane concentrations above 8% while ensuring safety and gradually lifting concentration restrictions on the direct combustion of low-concentration drainage methane. Additionally, CMM recovery should be integrated into the CCER market, with improvements in the methodologies for CMM utilization projects. Favorable land and tax policies can also be provided to support project development.

Sustain efforts to drive technological innovation and scientific research to break through bottlenecks and resolve key challenges. China has created its CMM recovery and utilization technology system, but some of the current technologies still face challenges in terms of methane concentration, safety, and energy efficiency. Looking ahead, the performance of key technologies can be improved and optimized to address the concentration limitation of the technologies and further reduce safety risks. At the same time, greater research funding can be allocated to emerging technologies (such as abandoned mine methane recovery technologies) to strengthen the assessment and development of CMM resources, along with pilot projects and engineering demonstrations. Under the existing technical framework, efforts can also be made to enhance methane concentration at the source by exploring CMM enrichment and permeability enhancement technologies. This would help reduce methane leakage from ventilation systems, expand the technical options available for utilization, and lessen the difficulties associated with recovery and utilization.

Deeply expand consumption channels and steadily improve downstream consumption. CMM recovery and utilization technology mainly relies on revenue from energy sales and the CCER market. Certain barriers exist in the sales of power generation, heat supply, and gas pipeline transportation, and taking appropriate measures to overcome the barriers will help promote and apply the technology. Among these barriers is a lack of access to the grid for CMM power generation and pipeline transportation. Local governments as well as power grid and urban gas enterprises can provide power access and grid connection support for CMM recovery and utilization technology, allowing CMM power generation projects to successfully enter the power market. In terms of heat supply, the existing CMM heating projects mainly satisfy the heat demand of coal mining enterprises themselves. The next step is to encourage the creation of a model that also enables consumption by neighboring markets. This will reduce the energy cost of mines while expanding the application of CMM heating in the neighboring regions through the market.

Strengthen support through transition finance and optimize project management. The up-front investment requirement for CMM recovery and utilization is RMB 100 billion. CMM recovery and utilization projects, are confronted with high up-front costs with long payback periods and lower return on investment. Transition finance serves as a critical market mechanism to decarbonize carbon-intensive industries, providing the necessary financial support for coal mines' decarbinization. Currently, China's transition finance system is in the research and exploration stage. By establishing financial standards for the coal industry's transition based on existing frameworks, China can increase support for methane mitigation projects, such as CMM recovery and utilization. Transition bonds can also alleviate financial pressure and boost corporate participation. At the same time, while ensuring legal and audit compliance, coal mining enterprises can also work with private capital, for example, by adopting the energy management contracting (EMC) model, whereby a specialized CMM utilization enterprise provides services to coal mining enterprises, including program design, equipment procurement, installation and commissioning, and operation and maintenance. Both parties can share the costs and benefits of the projects, achieving a win-win cooperation.

Build an international cooperation platform to jointly promote methane emission reduction in developing countries. CMM recovery and utilization projects possess great carbon reduction potential and energy value. China has accumulated valuable experiences in terms of technology research and development, project construction, and operation. Certain developing countries have energy structures and resource endowments similar to China, highlighting an urgent need for support and expertise in methane reduction. Building on South-South cooperation on climate change and the green development goals of the Belt and Road Initiative, China could further strengthen international collaboration and technology exchange in methane mitigation. This includes assisting coal-dependent developing countries in their efforts to reduce methane emissions through the recovery and utilization of ventilation air methane (VAM), low-concentration drainage methane, and abandoned mine methane. Additionally, China can support these countries in developing tailored technological solutions and cooperation frameworks suited to their specific resource endowments and economic needs. Through joint development, technology training, and experience sharing, China's efforts will enhance developing countries' capacity to tackle climate change and accelerate their low-carbon transition.

Appendix: List of CMM Recovery and Utilization Technologies

Emissions source	Applicable concentration	Technology	Principles	Representative enterprises/ organizations (in no particular order and non-exhaustive)	Maturity
Ventilation system[ii]	0.3%–0.75%	Ventilation air methane (VAM) regenerative oxidation	The Regenerative Thermal Oxidizer (RTO) is used to oxidize the VAM in a flame-free environment at a high temperature of about 600°–900°C while releasing heat. Waste heat boilers are used to recover high-temperature and high-pressure steam, which can be used to supply heat or drive generator sets to produce electricity. [18]	Shandong Shengdong Group, Xi'an Yuchang Environmental Technology Co., Beijing Yangde Environmental Energy Technology Co., Zichai Power Co., Zhejiang Yiyang Energy Technology Co., DURR, Eisenmann, Anguil, Harworth.	TRL 4–6
	0.3%–0.75%	VAM catalytic oxidation	The principle is similar to regenerative thermal oxidation. With catalysts, the methane in the ventilation air can be oxidized at a lower temperature (about 350°C) to release heat energy,[19] which can then be used for heat supply or power generation.	CAS Shanxi Institute of Coal Chemistry, Shandong University of Science and Technology, CSIRO (Commonwealth Scientific and Industrial Research Organization), CANMET (Canadian Centre for Mineral and Energy Technology).	TRL 4–6
Drainage system Low-concentration drainage methane	1%–3%	Mixing oxidation with VAM	Low-concentration drainage methane and VAM are mixed to about 1.2% and sent to the generative thermal oxidizer or catalytic oxidizer. VAM is oxidized to produce heat. The waste heat can be used for power generation or heat supply.	Same as VAM	TRL 4–6
	3%–8%	Direct combustion for heat production	Drainage methane is directly fired to generate hot steam using waste heat boilers. The difficulty increases as gas content lowers. Direct combustion includes super-enthalpy combustion, porous media combustion, and others.	Anhui University of Science and Technology, Shanxi Gaochuang Energy New Technology Co., Beijing Junfa Energy Saving and Environmental Protection Technology Co.	TRL 3–5
	8%–30%	Power generation/ cogeneration	Internal combustion engines are used for power generation after mixing drainage methane with air. This requires additional safety measures because CMM with a low concentration of 5%–16% poses a risk of explosion.	Shengdong Group., CNPC Jichai Power Co., Zichai Power Co., Shandong Lvhuan Power Equipment Co.	TRL 7–9
	15%–30%	Low-concentration drainage methane concentrating	Purification and concentration methods are used to increase the concentration of low-concentration drainage methane to over 30%. Vacuum pressure swing adsorption is the technique showing the best results.	Sichuan DKT Energy Technology Co., CCTEG Coal Mining Research Institute, Huainan Mining Group.	TRL 4–6

Continued on next page

ii Note: Although certain VAM utilization technology developed by some enterprises is applicable to coal mine methane with the lowest methane concentration of 0.2%, we concluded that the concentration should be greater than or equal to 0.3% to ensure stable operation of the equipment.

Continued from previous page

Emissions source	Applicable concentration	Technology	Principles	Representative enterprises/ organizations (in no particular order and non-exhaustive)	Maturity
Drainage system High-concentration drainage methane	>30%	power generation/ cogeneration	High-concentration drainage methane is used as a fuel for combustion. Power generation equipment is driven by steam turbine, gasturbine, or internal combustion engine to generate electricity. The waste heat can be sold as steam.	Shengdong Group., CNPC Jichai Power Co., Zichai Power Co., Shandong Lvhuan Power Equipment Co., Caterpillar, INNIO, MWM, DEUTZ.	TRL 7–9
	>30%	Concentrating for CNG/LNG preparation	The concentration of drainage methane is increased to more than 90% after purification and concentration process. The gas is prepared as CNG or LNG after compression.	CCTEG Coal Mining Research Institute, ChemChina, etc.	TRL 7-9
Abandoned mine methane	>30%	Industrial/ residential use (>40%)	The highly concentrated abandoned mine methane is collected and treated and then piped to towns and cities for civil use or used as fuel for gas boilers and industrial kilns.	Jinneng Holding Group, Yanquan Coal Industry Group, etc.	TRL 7–9
	>30%	Surface extraction and utilization	Graded extraction and utilization are implemented based on the difference in methane volume fraction in underground abandoned mines. This applies to surface wells to extract methane from the worked-out section for utilization.	Huaihe Energy Group, DEUTZ, Green Gas DPB, Alkane Energy, Vessels Coal Gas (VCG)	TRL 1–3

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