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UNDERSTANDING COAL MINE METHANE SOURCES AND MITIGATION OPPORTUNITIES IN SHANXI PROVINCE

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UNDERSTANDING COAL MINE METHANE SOURCES AND MITIGATION OPPORTUNITIES IN SHANXI PROVINCE

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Methane (CH_4) is a potent and important greenhouse gas (GHG), which has an 80 times higher global warming potential than CO_2 in a 20 year time horizon (Byers et al., 2022). By 2024, more than 150 countries representing 45% of global methane emissions have pledged to reduce their methane emissions 30% by 2030 (Global Methane Pledge, 2022).

China is a major contributor to methane emissions, as the largest global emitter of anthropogenic methane (Global Methane Pledge, 2022). Global coal operations released over 40 Mt of methane emissions in 2022, nearly half of which came from China, the world's largest coal producer (International Energy Agency, 2023b). China has taken steps to mitigate emissions including issuing a National Action Plan on Methane Emission Control (Ministry of Ecology and Environment, 2023), and highlighting methane as a key area for collaboration with the U.S. through the Glasgow Joint Declaration (United States Department of State, 2021) and Sunnylands Statement (United States Department of State, 2023).

Shanxi province in China is a major coal producing region and plays a significant role in China's GHG emissions. Shanxi accounts for around 13% of total national methane emissions (Liu et al., 2021), and about 30-35% of national coal mine methane (CMM) emissions (Sheng et al., 2019). According to several global inventory estimates, methane emissions from Shanxi are 31-36% higher than emissions in the second highest emitting province (Yu et al., 2022). Targeting high emitting regions and facilities present a policy opportunity for methane mitigation. While several recent studies have evaluated CMM emissions specifically in Shanxi province (He et al., 2024; Peng et al., 2023; Qin et al., 2024; Zhang et al., 2023), CMM emissions and mitigation options are uncertain, given that both are highly dependent on the local conditions of coal mining operations and type of mine (underground vs. surface), in addition to the magnitude of coal production.

This research identifies sources of CMM emissions in Shanxi, investigates energy production and policy trends in the region, and highlights opportunities for mitigation. In Shanxi, almost all coal produced is from underground mines (Peng et al., 2023), so this analysis will primarily focus on underground mining.

COAL MINE METHANE IN SHANXI

COAL MINE METHANE

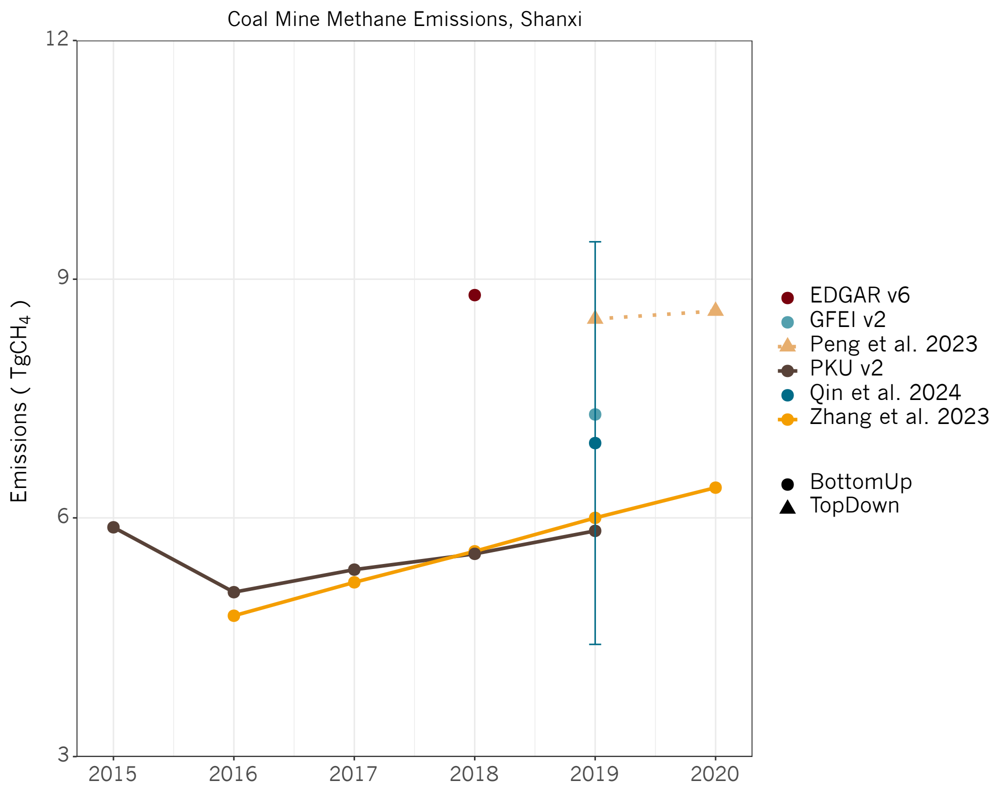
Coal mine methane (CMM) refers to the methane released from coal and the surrounding rock strata and coal seams from mining activities (National Energy Administration, 2018; United States Environmental Protection Agency, 2015). CMM presents a safety concern, as it can create an explosive hazard to mine workers, and is thus removed from active underground mines. CMM emissions are a function of coal production activity, as well as coal mining depth, coal type and other factors. Methane is released by different types of mines: (1) Operating underground mines, where methane is released during drainage processes through degasification systems and/or ventilation systems; (2) Operational surface mines and (3) abandoned or decommissioned mines, which emit abandoned mine methane (AMM) (United States Environmental Protection Agency, 2015). Coal bed methane (CBM) is coal seam methane that is not found in mining areas and hasn't been mined yet (United States Environmental Protection Agency, 2015).

Methane emissions estimates

Methane emissions are highly uncertain, unlike CO_2, given the influence of local conditions on methane emissions. A number of recent studies have highlighted the differences in global and national methane emissions estimates that use different methodologies (Deng et al., 2022; Lin et al., 2021; Petrescu et al., 2024; Tibrewal et al., 2024), suggesting that emissions may not be accurately captured when using global or nationally aggregated emission factors. Additionally, prior research suggests that global estimates may not be reflective of the locations of methane emissions, including coal mines in Shanxi (Qin et al., 2024; Sheng et al., 2019). Also, prior analyses have highlighted the large variation in local conditions that impact emissions across regions, emphasizing the challenges with using a single emission factor for a province (Peng et al., 2023). This analysis collected estimates for Shanxi province from global and national inventories as well as literature focused specifically on Shanxi province. Estimates range from 5.8 Tg CH_4 to 8.5 TgCH_4 in 2019 (Figure 1), with global inventories and the only analysis with satellite observations collected on the higher end, and national and Shanxi specific bottom-up estimates on the lower end. One estimate suggests emissions may even range from 4.4 to 9.5 Tg CH_4 (Qin et al., 2024). Estimates with multiple years of data suggest that emissions are increasing over time.

FIGURE 1. CMM EMISSIONS ESTIMATES IN SHANXI.

Top-down estimates (using atmospheric or satellite measurements) are noted with a triangle symbol, while bottom-up estimates (using activity data and an estimated emission factor) are circles. Non-time series data is noted with a dashed, not solid line. One source provided a range of potential emissions estimates in 2019, which is noted with an error bar and a mean value. Sources: (Ferrario et al., 2021; Liu et al., 2021; Peng et al., 2023; Qin et al., 2024; Scarpelli & Jacob, 2021; Zhang et al., 2023).



Additionally, little is known about emissions from AMM in Shanxi. According to statistics from the Department of Natural Resources in 2020, the goaf area (area that has been mined) in Shanxi province is currently more than 5,000 km2, which includes more than 4,700 abandoned mines (Xinhua News, 2020). Research suggests that country specific data on the mine type, depth, flooded status, gas content, and more is needed to better understand the magnitude and trend of AMM emissions at the national or provincial level, especially as the number of closed mines increases in the future (Kholod et al., 2020).

Factors influencing coal mine methane emissions

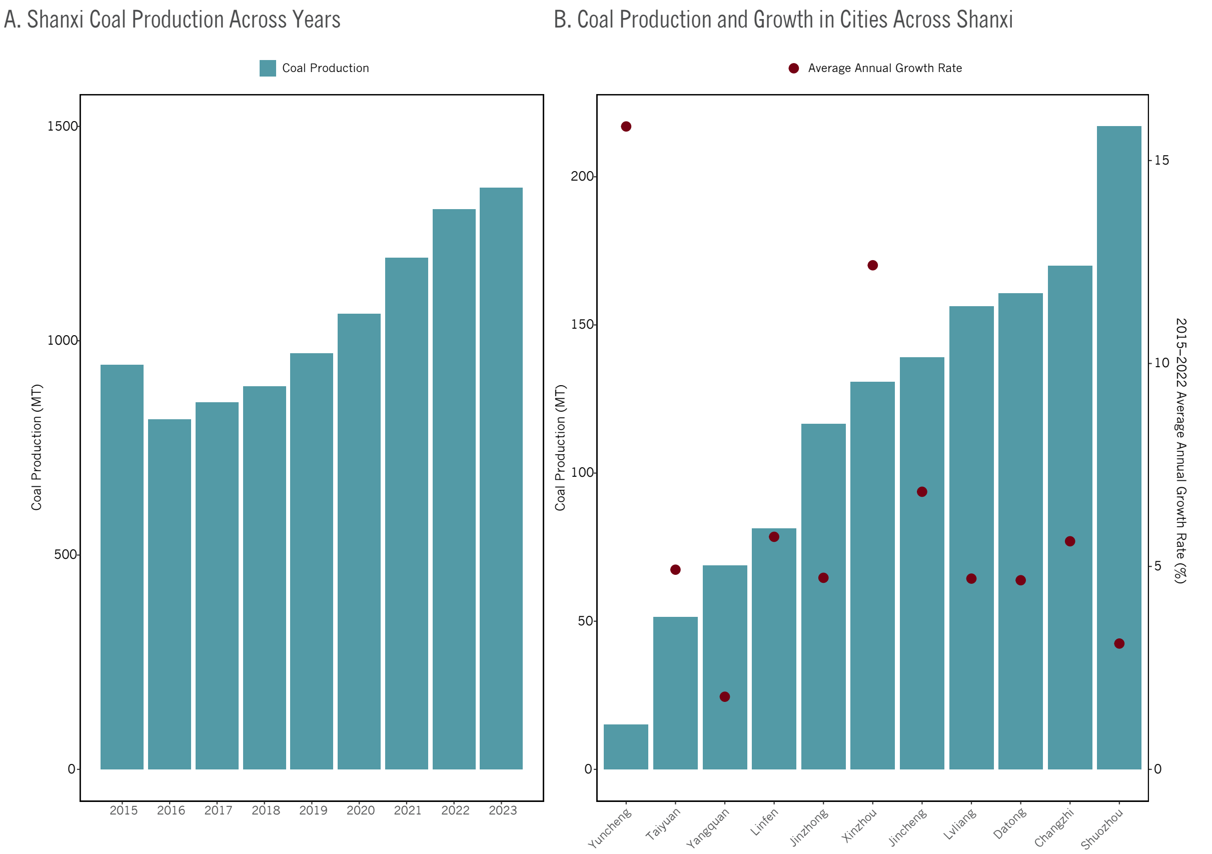
Better understanding the variation in coal mining activity and the local conditions that impact methane emissions across the province is needed to estimate methane emissions and inform policy recommendations.

Coal production

Shanxi is one of China's largest coal-producing regions. Shanxi was the largest coal producing province from 2020-2023 and accounted for almost 30% of national production in 2023 (National Bureau of Statistics of China, 2024). From 2015 to 2023, production increased by 44%, reaching 1.357 billion tons (National Bureau of Statistics of China, 2024; Shanxi Bureau of Statistics, 2022) (Figure 2). Demand increases in both Shanxi and other provinces, potentially due to the pandemic, coal supply shortage and growth in industries such as coking, metallurgy, and steel, may be driving increased production. Around 50% of coal produced in Shanxi was consumed outside the province from 2015-2022 (Shanxi Bureau of Statistics, 2023).

FIGURE 2. COAL PRODUCTION IN SHANXI. A) COAL PRODUCTION IN SHANXI FROM 2015-2023; AND B) COAL PRODUCTION IN 2022 AND AVERAGE ANNUAL GROWTH RATE OF COAL PRODUCTION FROM 2015-2022 ACROSS CITIES IN SHANXI.

Source: (Shanxi Bureau of Statistics, 2023).



Coal resources in Shanxi are mainly distributed in the north, central-west and east (Figure 3). The majority of coal production comes from two main areas: the Datong and Ningwu coalfields in northern Shanxi and the Qinshui coalfield in eastern Shanxi. These two areas accounted for 39% and 38% of total production in 2022, respectively (Shanxi Bureau of Statistics, 2022). In west-central Shanxi, three major coal fields, Hedong, Huoxi and Xishan account for approximately 22% of the province's production in 2022 (Shanxi Bureau of Statistics, 2022). Shuozhou is the largest coal producing city, with more than 200 million tons produced in 2022 (Figure 2). Most other cities produced over 100 million tons in 2022, except for the 4 lowest producing cities. All cities have increased production since 2015, with the fastest growth occurring in Xinzhou and Yuncheng. Coal production in Xinzhou may be increasing due to a series of policies which include reducing taxes on coal mining (Government of Xinzhou, 2015, 2021), in order to reduce costs and improve production efficiency. Yuncheng has limited coal resources but the development of heavy industry in the city has recently boosted the demand for coal consumption and promoted the development of local coal resources (Government of Yuncheng, 2022).

Coal mine characteristics

A large number of factors and local conditions impact CMM emissions from coal production activity. Methane emissions vary based on the geology, depth of the mine, and characteristics of coal in a region (Gao et al., 2020; Liu et al., 2021; Zhang et al., 2023; Zhu et al., 2017), making incorporating detailed mine information critical for developing accurate CMM estimates. Deeper coal beds, older mines and underground mines tend to contain more methane (International Energy Agency, 2023a). Methane emissions intensity, the magnitude of emissions per unit of output, varies across coal types by coal ranking or coalification (United States Geological Survey, 2024), with anthracite having the highest emissions intensity, followed by meager coal, lean coal, coking coal, fat coal, gas coal, and weakly caking coal (Institute of Geographic Sciences and Natural Resources Research, 2006; Peng et al., 2023). Other factors influencing methane emissions include water content and geological structure. Higher coal water content results in lower absorption capacity and, therefore, higher methane emission rates (Tian et al., 2017). Also, certain geological structures including tectonic uplift, stratum losses, and erosion can aggravate methane gas leaks, which is the case for the northern part of Shanxi (Li et al., 2022). In Shanxi, most mines are underground, with a maximum depth greater than 300m ((Institute of Geographic Sciences and Natural Resources Research, 2006; Peng et al., 2023).

To evaluate methane emissions from underground mines in the region, both coal production and methane emissions intensity need to be considered. Methane emissions may be highest in Changzhi and Jincheng, given the high rates of coal production and the presence of geological factors that contribute to higher methane emissions (Figure 3). Both cities have anthracite coal and the deepest coal mines (~600m) (Peng et al., 2023). Other cities in the Qinshui coalfield have lower levels of production, but still relatively deep mines and high coalification. Therefore, cities in the Qinshui coalfield overall may emit more methane per unit of output than other cities in Shanxi. Lvliang has higher levels of production than Jincheng, but lower coal mining depth and coalification, as do Shuozhou and Datong, which have limited mine depth (~300m) (Peng et al., 2023). However, methane emissions may be similar given the high levels of production. This highlights the need for future methane emissions assessments to account for differences in methane emissions intensity along with coal production levels across regions in Shanxi.

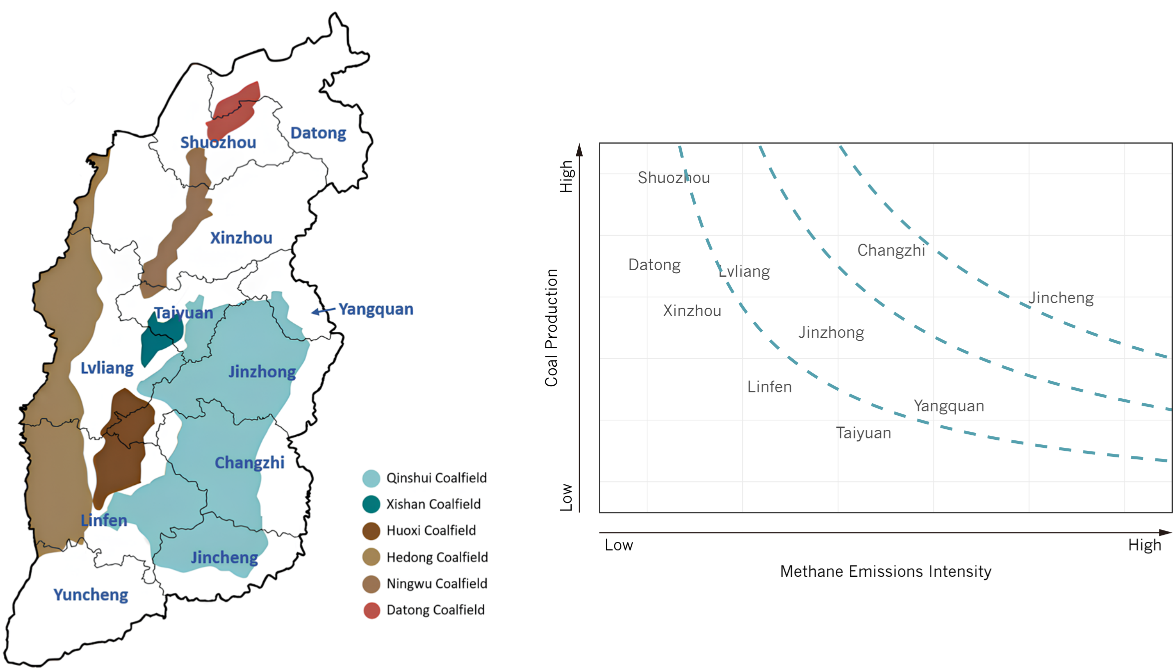
Based on this analysis, prioritizing mitigation in the Qinshui coalfield and surrounding cities may help mitigate emissions in Shanxi. Other research that incorporates mine specific information supports that the Qinshui coalfield and surrounding areas are major sources of methane emissions in Shanxi (He et al., 2024; Peng et al., 2023; Zhang et al., 2023). Additionally, this region has a higher proportion of coal and gas outburst mines, which have a higher methane emission concentration compared to high gas mines (Zhang et al., 2023). Also, prioritizing mitigation in Shuozhou, Datong and Lvliang, given high levels of production, is needed. More site based data is needed to make more informed decisions about methane mitigation, and inform technology deployment across cities depending on methane concentrations and how scale-dependent technologies are. Better understanding the concentration of methane emitted from mines is important for informing mitigation strategies.

FIGURE 3. COAL FIELD LOCATIONS AND RELATIVE EMISSIONS IN SHANXI. PANEL A: COAL FIELDS AND CITIES IN SHANXI SOURCES: (HU ET AL., 2020; WEBMAP, 2014); PANEL B: ESTIMATED RELATIVE METHANE EMISSIONS ACROSS CITIES IN SHANXI.

Cities along the same dashed lines are estimated with relatively equal CMM emissions, assuming that CMM emissions are equal to production times methane emissions intensity (please see appendix for additional details on methodology). Sources: Shanxi Bureau of Statistics, 2023; Peng et al., 2023 (with coal type originally from (Liu et al., 2015). Note: Methane emissions intensity only considers maximum coal mining depth and main coal type in each city. The relationship between mining depth and emissions varies across coal type (Kholod et al., 2020) but was not considered. Other factors could contribute to methane emissions intensity beyond those evaluated.

A

B



MITIGATION POTENTIAL AND POLICY OPTIONS

Mitigation opportunities and challenges

Mitigation opportunities are highly dependent on coal production, coal mine characteristics, mining depth and methane gas concentrations (Table 1). Current mitigation measures for CMM include reducing coal production, capture and utilization, direct flaring and oxidation (International Energy Agency, 2023d; Zhou et al., 2023). While reducing coal production would be a major driver of emissions reduction, it is the result of a variety of other political and economic factors, so this analysis will focus on other mitigation measures with a focus on near-term mitigation opportunities. Due to the huge potential for the utilization of CMM and potential economic benefit as an energy source, most mitigation efforts focus on extraction and utilization, which captures ventilated CMM and uses it as an energy resource, similar to natural gas.

The major extraction methods of CMM are underground methane extraction (extraction during coal mining), surface pre-drainage (extraction before coal mining), surface and underground joint extraction, and extraction after coal mining, which require the combination and coordination of techniques (Ji et al., 2024; Zhou et al., 2016). In China, it is mandatory to implement pre-drainage to reduce the gas pressure and content below a safety threshold (State Administration of Coal Mine Safety of China, 2016) and the direct emission of high-concentration CMM is prohibited (Ministry of Ecology and Environment, 2023). The concentration of CMM extracted from pre-drainage is relatively high, usually above 95%, which can be utilized directly (Zhou et al., 2016). CMM from underground methane is usually of lower concentration, and is mainly utilized in the coal mines or vented.

In China, extraction of CMM from underground mines can be a challenge, given the high gas pressure, strong gas adsorption, and low permeability of coal seams (Zhou et al., 2016). The cost of producing CMM is currently more than twice the cost of conventional gas in China (China Energy News, 2021; Ping An Security, 2020), and while national subsidies have helped (National Energy Administration, 2021), they haven't reduced the price enough to make it competitive (Shanxi Natural Gas Utilization Association, 2024). An additional challenge for CMM extraction is the development of infrastructure to transport CMM. Without a network of pipelines for transporting CMM from mines to locations for utilization, CMM must be either used on site or vented. In recent years, China has made progress in safe transportation and use of low-concentration methane in internal combustion engines, which improved the utilization of methane at concentrations above 6% (Wang et al., 2021a). Additionally, Shanxi is developing pipeline and transportation networks for transmission of CMM, with the length of pipelines increasing by 25% in 2022 compared to 2015, and capacity increasing to 30 billion cubic meters per year by the end of 2022 (Government of Shanxi, 2016b; Shanxi Natural Gas Utilization Association, 2024). However, additional transportation options need to be developed in the future, especially for low-concentration CMM.

Overall, utilization has been increasing in Shanxi for both surface and underground mining. The surface utilization rate increased from 85% in 2014 (Xu, 2017) to 94% in 2020 (Zhongtai Securities, 2021) and underground utilization increased from 32% in 2014 (Xu, 2017) to 45% in 2020 (Zhongtai Securities, 2021). Some research suggests that methane emissions may be declining in Shanxi, potentially due to the increasing utilization (Zhang et al., 2022).

TABLE 1. CMM CONCENTRATIONS.

Sources: (Wang et al., 2021a).

High-concentration Methane	Ultra-high (90-100% vol CH_4)
	Mid-high (30-90% vol CH_4)
Low-concentration Methane	Mid-low (6-30% vol CH_4)
	Ultra-low (1-6% vol CH_4)
Ventilation Air Methane (VAM)	(0-0.75% vol CH_4)

However, utilization methods vary across concentrations of CMM (Table 1) and additional strategies are needed to expand utilization of low-concentration methane. Technologies for utilizing high-concentration methane (concentration above 30%) are relatively mature, and can be utilized as domestic/industrial fuels, or to generate electricity by internal combustion engines (Wang et al., 2021a). Safety risks, high costs and current technology options limit the use of low-concentration methane (concentration 1-30%), leading to high levels of CMM discharge of this type of methane (United Nations Economic Commission for Europe, 2016; Wang et al., 2023). Currently, approximately 55% of low-concentration methane and the majority of Ventilation Air Methane (VAM) (concentration <1%) are directly released into the atmosphere in China (Wang et al., 2021a). VAM utilization is difficult, due to the low and unstable methane concentrations and high volume rate (Wang et al., 2021a). Currently, it is mainly utilized on-site or vented, requiring processing such as blending or purification for utilization. Technologies are in development to both stabilize methane concentration, remove impurities and enable utilization, but utilization at <6% concentration is still in the demonstration stage and is not widely used (Wang et al., 2021a). In assessments of mitigation potential in China, VAM oxidation has the highest emissions abatement potential, followed by degasification for power generation, open flaring and degasification for pipeline injection, highlighting the importance of low-concentration methane mitigation (United States Environmental Protection Agency, 2024). Other analyses support VAM oxidation as playing a key role in global mitigation efforts, along with CMM drainage and utilization (International Energy Agency, 2023c). Of the CMM extracted in China, VAM may account for 76-83% of total (Zhou et al., 2020; Zhou et al., 2016), making utilization of VAM an important issue to address.

MAJOR ACTORS AND INDUSTRIES IN CMM UTILIZATION

In China, coal mining rights and CMM/CBM extraction rights are separate, creating barriers for businesses to conduct extraction and utilization, since coal mines and CMM are spatially overlapped. CMM/CBM mining rights mostly are owned by central government-owned oil & gas enterprises, while coal mining rights are held by provincial government-owned coal enterprises. In Shanxi, there are seven major coal producers, which are all state-owned enterprises (SOEs) (Zhongtai Securities, 2019). The overlapping of mining rights across industries can be problematic, as industries have different incentives and priorities. For example, CBM extraction activities by oil & gas companies could impact geological structure and later coal mining activities, while coal companies may not prioritize capturing CMM released during mining. Shanxi launched a series of policies to ease this problem, proposing guidance for negotiation in overlapping areas, promoting competitive transfer of mining rights, and suggesting mechanisms for the withdrawal of CMM/CBM mining rights from companies failing to meet the extraction volume threshold (Department of Natural Resources of Shanxi Province, 2017, 2021, 2022; Government of Shanxi, 2016a). However, some of the policies are still in the pilot stage and the process of transferring CMM/CBM extraction rights is still complex.

Policy trends

China has been enacting regulations and standards to address methane emissions in the coal sector since 1952, including on maintaining safe methane concentration levels, recovering and utilizing CMM/CBM, and prohibiting venting above certain thresholds (Yu et al., 2022). Recently, China has released a series of policies focused on CMM, including monitoring methane emissions, as well as subsidies and tax incentives for CMM utilization (Ministry of Ecology and Environment, 2023; Ministry of Finance, 2019). China has also released a National Action Plan on Methane Emission Control, which established a utilization target of 60 billion cubic meters by 2025 (Ministry of Ecology and Environment, 2023).

Shanxi has launched a series of policies to regulate CMM extraction and incentivize CMM utilization including a target that by 2025, the underground utilization rate will exceed 50% and utilization will reach 5.5 billion cubic meters per year (Government of Shanxi, 2023d). Currently, Shanxi has not conducted large-scale AMM utilization, and the utilization methods are still unclear. However, the Shanxi government has issued a series of policies providing support for AMM utilization pilot construction and integration of AMM into the natural gas network (Government of Shanxi, 2019a, 2023d).

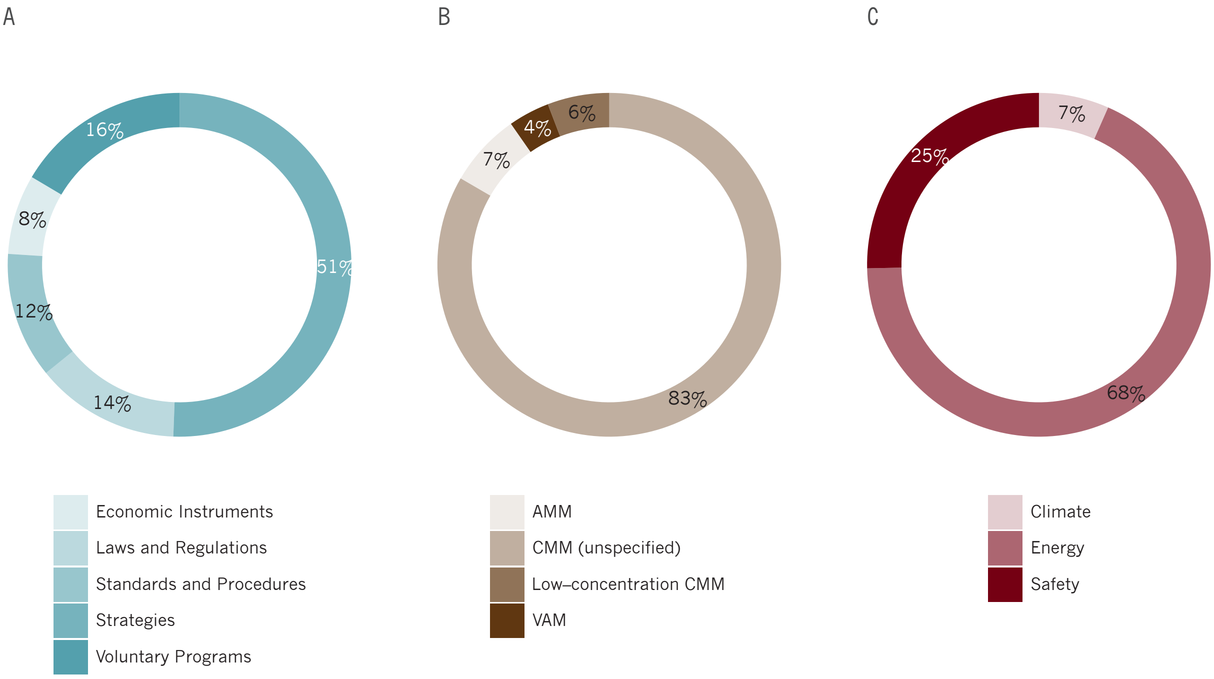
Provincial policy analysis

Based on policies collected by February 2024 (see additional information in the appendix), there are a variety of policy instruments adopted in Shanxi (Figure 4). Strategies, such as the Shanxi Coal Industry Development 14th Five-Year Plan and the Shanxi Province Low-Carbon Innovation Action Plan, are the most often adopted tool, accounting for 51% of the policies collected (Government of Shanxi, 2014, 2023c). These policies give overall guidance, design high-level plans and set targets for CMM extraction, capture and utilization. Voluntary programs are occasionally adopted for CMM mitigation (16%), including some national key innovation programs (Government of Shanxi, 2023a). Laws and regulations and standards and procedures comprise less than 15% of total policies each, and are implemented primarily to regulate mining methods, mineral exploration rights, mining rights transfer, and land recovery and utilization. The provincial government also provides economic-based incentives including offering funding, encouraging market-based solutions, and giving tax exemptions and subsidies. For instance, the Notice on Issuing

Shanxi Province's Measures to Address Climate Change encourages the development of the CMM industry and implements exploration and mining rights fee reduction and exemption policies for surface extraction projects. The government also gives tax deductions for CMM extraction and other comprehensive utilization projects (Government of Shanxi, 2011). However, support has been limited as this is the least commonly deployed instrument (8%).

FIGURE 4. POLICY DISTRIBUTIONS BY POLICY INSTRUMENT, POLICY FOCUS AND CMM TYPES OF SHANXI.

Sources: (Department of Natural Resources of Shanxi Province, 2024; Government of Shanxi, 2024; PKULaw, 2024; Shanxi Development and Revolution Commission, 2024; Shanxi Provincial Energy Administration, 2024) (please see appendix for additional details on methodology).



Most policies in Shanxi don't have a focus area within CMM (Figure 4). Only around 20% of policies collected specifically focused on VAM, AMM, or low-concentration CMM, with remaining policies focused on CMM generally. The Shanxi government launched an AMM policy in 2019, the Notice on Matters Related to Coalbed Methane Drainage Tests in Coal Goaf Areas (Abandoned Mines), which highlights the energy value of AMM (Government of Shanxi, 2019b). However, Shanxi does not have many other policies targeting AMM regulation.

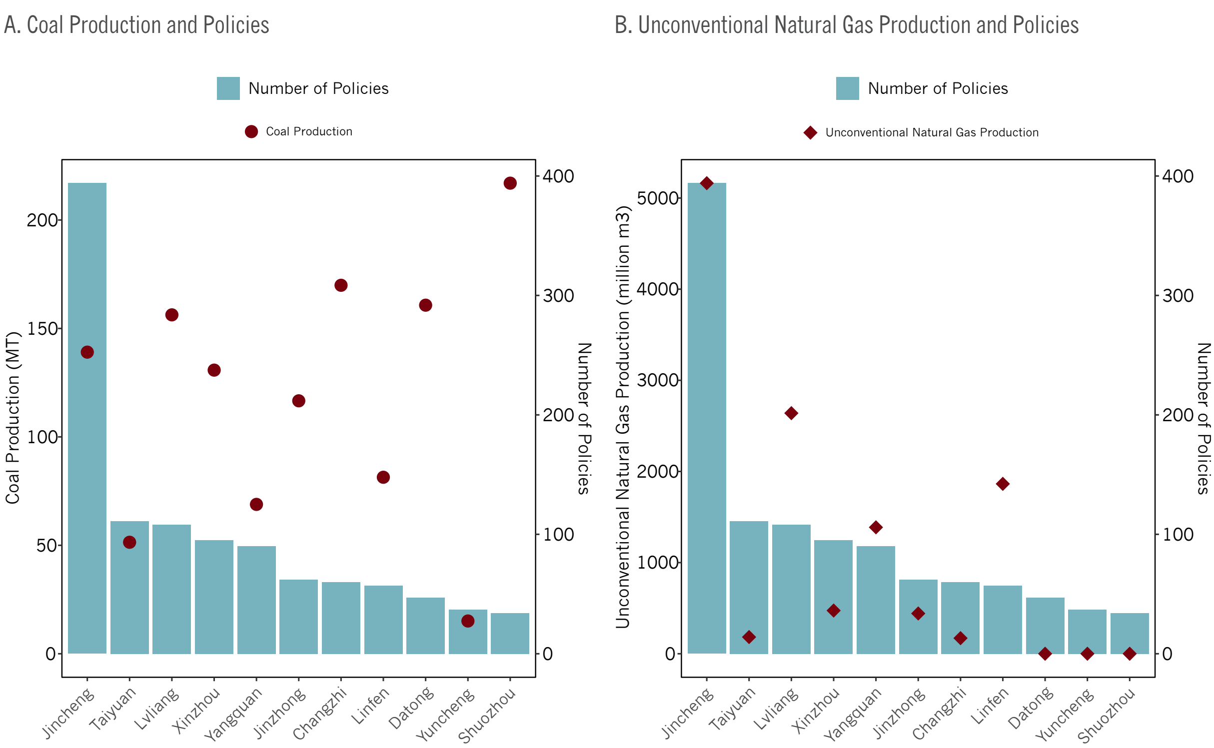
Across policy focus areas, there are a number of priorities in Shanxi (Figure 5). Most of the policies (68%) focus on the energy usage of CMM (both surface and underground), emphasizing CMM's potential role in the circular economy, energy conservation, and clean energy development. For example, in the Guiding Opinions on Promoting Comprehensive Utilization of Coal Mine Gas', the government encourages comprehensive utilization (Shanxi Provincial Energy Administration, 2022). Around 25% of policies collected focus on safety concerns, and the earliest policy collected regulates CMM for safety reasons, highlighting the importance of this issue (Government of Shanxi, 2003). Additionally, CMM-related policies also focus on regulating CMM as a major driver of climate change, especially after the announcement of the dual-carbon goals in 2020, mostly by promoting VAM and low-concentration methane utilization and discouraging direct venting, such as the Shanxi Province Low Carbon Innovation Action Plan, the Opinions on Promoting Green Coal Mining in the Province and the Shanxi Province Carbon Peak Implementation Plan (Government of Shanxi, 2014, 2022, 2023b). But, only 7% of the total policies collected focus on climate concerns, suggesting this is an area that requires additional policy focus. Policy priorities have changed over time, with policies initially focusing on CMM safety, then increasingly on energy and utilization, followed by more recent climate policies.

City-level policy analysis

In Shanxi, the number of CMM policies in each city may align more closely with unconventional natural gas production than coal production trends (Figure 5). Jincheng, with the highest production of unconventional natural gas, has implemented the most CMM-related policies compared with other cities. Conversely, cities like Shuozhou and Datong, which have high coal production but limited unconventional gas production, have noticeably fewer CMM policies, suggesting the potential influence of industry on CMM policies across Shanxi's cities.

FIGURE 5. A) CMM POLICIES IMPLEMENTED (SINCE 2007) AND COAL PRODUCTION IN 2022 ACROSS CITIES IN SHANXI; AND B) CMM POLICIES IMPLEMENTED (SINCE 2007) AND UNCONVENTIONAL NATURAL GAS PRODUCTION IN 2022 ACROSS CITIES IN SHANXI.

The level of coal production here is a proxy for methane emissions, although it doesn't include additional factors that impact methane emissions as discussed above. Looking at coal production, as a source of CMM emissions, along with enacted CMM policies can help to identify policy trends. Natural gas production data not available for Yuncheng. Sources: (PKULaw, 2024; Shanxi Bureau of Statistics, 2022) (please see appendix for additional details on methodology). Note: Natural gas production data for Yuncheng was not available.



City-level policies in Shanxi have several key focus areas, including:

Safety supervision. Local governments also regulate CMM from a safety perspective, including mine safety, pipeline management, transportation security, storage supervision, and terminal use safety, so as to control gas concentration, reduce leakage, prevent accidents, and conduct gas management (24%). For example, the Shuozhou Notice on Further Clarifying the Responsibilities for the Protection and Safety Supervision of Oil and Gas Pipelines emphasizes the importance of transportation and production safety (Government of Shuozhou, 2015b).

Program development. The municipal government actively promotes programs related to the collection and utilization of CBM/CMM, focusing on specific companies, projects, and regions to advance project progress and implementation (17%). For example, the Jinzhong Energy Development Strategy Implementation Plan specifically proposes plans in areas such as Shouyang District, Heshun District, and Xiyang District, including key programs such as the 100,000-ton low-concentration CMM purification and liquefaction project in Shouyang County (Government of Jincheng, 2015).

Industry development. City-level governments have implemented guidance and requirements, financial incentives and investments for the development of the CBM/CMM industry (13%). For example, in the Lvliang Implementation Opinions of the Development Plan for the Utilization of Coalbed Methane (Natural Gas), requirements have been made regarding exploration and extraction, pipeline construction and urban gas supply (Government of Lvliang, 2015b). Additionally, Shuozhou offers policy incentives such as subsidies in the Shuozhou Interim Measures for the Use and Management of Special Funds for Technological Transformation (Government of Shuozhou, 2019). Lvliang City also set a target of investing 5.1 billion yuan ($800 million in 2015) in CBM extraction and exploitation in the Implementation Plan for the Project Quality and Efficiency Improvement Year (Government of Lvliang, 2015a).

Air pollution control. Some local policies also emphasize the role of coalbed methane as a clean energy source compared to traditional energy in mitigating atmospheric pollution, thereby encouraging CMM collection and utilization to ease contamination (8%). For example, the Linfen Air Pollution Prevention and Control 2015 Action Plan, Yangquan Air Pollution Prevention and Control Action Plan and Lvliang Three-year Action Plan for Winning the War to Protect Blue Skies include the use of CMM/CBM in the municipal heating system as a way to reduce air pollution (Government of Linfen, 2015; Government of Lvliang, 2018; Government of Yangquan, 2013).

Organization management. The municipal government has also undertaken administrative reform to better regulate CMM/CBM (5%). This involves assigning management and supervision tasks to more specific departments and offices. For instance, the Shuozhou Main Responsibilities Internal Organization and Staffing Regulations assigns the management of the coalbed methane industries, implementation of industry development plans, and development of relevant policies to the Regional Economic Office of Municipal Development and Reform Commission (Government of Shuozhou, 2015a).

Climate mitigation. Municipal governments also regulate CMM in the overall campaign of mitigating climate change by promoting the utilization of low-concentration CMM, encouraging the development of VAM utilization technology, facilitating AMM exploration and utilization, and advancing the collection of vented CMM (4%). For instance, policies such as the Shuozhou 13th FYP for Climate Change Response, the Xinzhou 13th FYP for Controlling Greenhouse Gas Emissions, and the Lvliang Carbon Peak Implementation Plan focus on the collection and utilization of CMM and its importance to climate change mitigation (Government of Lvliang, 2023; Government of Shuozhou, 2018; Government of Xinzhou, 2018).

Technology innovation. The municipal government also focuses on technological innovations related to the development and utilization of CMM, particularly emphasizing innovations such as the extraction of methane from abandoned mines, low-concentration gas power generation, low-concentration gas purification, and VAM catalytic fuel (3%). For example, the Xinzhou Implementation Plan of Innovation-driven Development Strategy set the strategy of developing CMM extraction and utilization technologies to increase utilization efficiency (Government of Xinzhou, 2017).

JINCHENG COAL MINE METHANE POLICIES

Jincheng has passed the most policies regulating CMM extraction and utilization in Shanxi, almost four times the next largest city (Figure 5). Jincheng's coal resources are considered the most explored, with the highest development potential and most mature commercial utilization in the domestic CMM industry. As of 2022, Jincheng has cumulatively extracted 41.6 billion cubic meters of CMM, accounting for 69% of Shanxi's total CMM extraction and 52% of the national CMM extraction (Government of Jincheng, 2023). In the Opinions on the implementation of the Shanxi Province Coalbed Methane Resources Exploration and Development Plan (2016-2020), the Jincheng government sets comprehensive strategies for CMM development in Jincheng concerning exploration methods, mining rights conflict, land management and utilization channels (Government of Jincheng, 2017a). In the Notice on Issuing the Jincheng City 2016 "1533" Industrial Action Plan, the government highlights 30 CMM enterprises to construct a coal mine methane industrial cluster and outlines the areas of future policy support including infrastructure preparation, investment guidance, and administrative convenience (Government of Jincheng, 2016, 2017c). The Jincheng government also provides specific financial incentives such as rewards, loans, and special funds to companies to collect and utilize CMM. In the Jincheng City Industrial Transformation and Upgrading Development Fund Implementation Plan, the government establishes a special fund of 5 billion yuan ($760 million in 2017) to support key industries including extraction and utilization of coal mine methane (Government of Jincheng, 2017b).

POLICY RECOMMENDATIONS

Bridge knowledge gaps for CMM

- **Expand research and development for low-concentration methane.** Research and development is needed to improve and reduce costs for technologies to capture and utilize low-concentration methane from underground mines. Understanding ways for efficient gas extraction at increasing coal mine depths is needed, especially as coal production and mining depth increase. Development and testing of low-cost methane mitigation technologies and a better understanding of the mitigation costs and technical potential for utilization in Shanxi are needed. Increasing diversification of technology options for use of CMM is also important (Liu, 2024).
- **Increase the understanding of AMM emissions.** AMM is one of the major sources of anthropogenic emissions in China (Chen et al., 2022) and may increase with declining coal production through decarbonization efforts toward carbon neutrality (Liu et al., 2024). The geological conditions of abandoned mines are complex, and there are still many challenges in quantifying emissions,

as well as development and utilization. Technologies for the development of AMM are still at an early stage and the boundaries of many abandoned mines intersect with the scope of the mining rights of existing coal enterprises, but the qualification conditions for accessing enterprises are unclear, creating barriers to the use of AMM (Wang et al., 2021b).

- **Establish a more comprehensive MRV system and data-sharing platform.** Quantifying emissions from key coal mining areas and regions is essential for informing quantitative emissions reduction targets, utilization targets, and overall mitigation policies (Zhang et al., 2023). The Shanxi government should establish more accurate provincial-level and city-level emission factors and update the reporting scheme. Research should use locally optimized emission factors and geospatial infrastructure data (Lin et al., 2021) and mine-specific data on methane ventilation and utilization rates to improve emission factor estimates (Gao et al., 2020). More accurate and transparent data on the geospatial distribution of coal mining infrastructure and mine-specific data will help increase understanding of opportunities for methane collection, utilization, and mitigation (United Nations Economic Commission for Europe, 2016).

Build a more comprehensive policy instrument toolkit

- **Set quantitative targets for CMM mitigation.** Although there are strategic plans in place to regulate CMM emissions, China has not set any quantitative targets. Similarly, Shanxi lacks local targets for CMM mitigation. Setting a target specifically for CMM emissions reduction is needed (Zhang et al., 2023).

- **Update and harmonize CMM emission, collection, and utilization standards.** The latest national standard for CMM was released in 2008 (MEE, 2008). At the provincial level, there is inconsistency across different regions, departments, and programs. The Shanxi and national government should collect recent technology data, set local standards for CMM emissions, and harmonize the standards across different regions, departments, and programs (Ministry of Ecology and Environment, 2023).

- **Offer stronger economic-based incentives.** Increasing economic-based policy support for CMM extraction and utilization is needed, especially for low-concentration CMM from underground mines given the challenges with extraction and utilization. The government should offer more financial incentives and loan opportunities, establish special funds, provide price premiums, tax credits, and subsidies for emission reductions, encourage private investment, involve CMM in the carbon trading scheme, and construct a more favorable environment for investment (IEA, 2023a; Zhang et al., 2023). Additionally, researchers can share estimates about the cost of mitigation and returns on investment for utilization to help inform investors and industry actors (GMI, 2023).

- **Simplify the administrative procedures concerning mining rights.** Mineral exploration and mining rights is an issue for CMM extraction in Shanxi. The Shanxi government has made substantial efforts to ease this problem, but the administrative procedure is still long, discouraging businesses that don't have mining and exploration rights from participating in CMM extraction and utilization. Avoiding conflict between provincial and state government groups, as well as across coal mining and oil and gas companies is needed. Implementing pilot programs and simplifying administrative procedures may help avoid conflict between centrally state-owned enterprises with CMM mining rights and provincial government-owned companies with coal mining rights.

Develop targeted policy approaches

- **Promote policy development in super emitting regions.** There are several potential high-emitting cities, like cities in the Qinshui coalfield and high producing cities like Shouzhou and Datong, that can develop targeted policy approaches. City governments in this region should implement more policies focused on CMM safety, collection and utilization and climate impacts. Also, Xinzhou and Yuncheng, as cities with rapidly increasing coal production in recent years, need to focus on regulating increasing CMM emissions. Additionally, targeting the closure of high emitting coal mines may help to reduce emissions (GMI, 2023).

- **Bridge the policy gaps for AMM emissions.** Shanxi's current policy on AMM is still in the preliminary stage. The government should set detailed standards, expand pilot projects, and simplify administrative procedures for AMM mining rights to alleviate the uncertainty of future regulation of AMM.

- **Establish a regulatory system to increase the utilization of low-concentration methane.** The utilization rate of CMM in Shanxi has been increasing, but targeting VAM and low-concentration utilization is needed. Advancing research and technical innovations, establishing local mandates for reducing low-concentration methane emissions, collaborating with global industry pioneers, and leading pilot and model programs, especially in critical areas like the Qinshui coalfield, is needed. Additionally, for low-concentration methane streams that aren't economically feasible to utilize, policy frameworks should be devised to promote methane mitigation efforts.

CONCLUSION

Prioritizing near-term actions to reduce CMM emissions in Shanxi, and in other regions across the globe, is critical for achieving global mitigation goals. Our analysis suggests that methane emissions in Shanxi province are uncertain, and that additional mine-specific data is needed to understand the methane emissions within the province and inform mitigation strategies. Prioritizing policies in regions with deep mines and high gasification, such as cities in the Qinshui coalfield, along with focusing on areas with high levels of production and/or rapidly increasing growth (Datong, Xinzhou), could help to mitigate methane emissions from underground mines. A major barrier to mitigation for China and other countries is technology and cost limitations for extraction and utilization of low-concentration CMM. Increasing research into technology options and expanding policy mechanisms to incentivize further deployment is needed. Future research should investigate the share of high, medium and low-concentration methane in Shanxi province to inform mitigation strategies. Additionally, as coal production declines due to climate mitigation efforts, better understanding of AMM emissions in Shanxi is needed to improve AMM and CMM methane estimates.

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