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Assessing Methane Emissions From the Natural Gas Industry: Reviewing the Case of China in a Comparative Framework

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Abstract

Purpose of Review The aim of this paper is to explore methane emissions from China's fossil fuel industry compared with the USA and Canada, with a focus on the methane emission mechanisms, calculation methods, mitigation potential, and abatement technologies.

Recent Findings This paper explores the methane emissions from China's natural gas industry from a comparative perspective. The main conclusions are as follows: (1) methane emissions from the natural gas production phase are the largest in the whole natural gas supply chain. (2) When it comes to measurement and estimation methods, methane emissions in the gas industry in the USA and Canada typically achieve a Tier 3 level, while China tends to be at the Tier 1 and Tier 2 levels. (3) There is large mitigation potential for methane emissions from the natural gas industry. More effective waste reduction technologies like green well completion should be implemented in the production phase, especially in China. At the same time, more attention should be drawn to the need for leakage detection technologies of pipelines in all countries compared here.

Summary As a large methane-emitting country, China lags behind the USA and Canada in methane emission reduction. Therefore, Chinese scientists, policy makers, and entrepreneurs should pay attention to methane emissions. Stakeholders should enhance mitigation measures and leakage detection technologies in order to achieve climate targets.

Keywords Methane emissions · Natural gas industry · Mitigation potential · Comparative analysis

Introduction

Many countries are aiming to achieve net-zero greenhouse gas (GHG) emissions, often called carbon neutrality, in the next few decades. The European Union (EU) aims to achieve its net-zero emissions target by 2050 [1]. The USA also aims to achieve net-zero emissions no later than 2050 [2]. As the top carbon dioxide (CO_2) emitter, China has specifically stated a goal of achieving carbon neutrality by 2060 [3]. However, in addition to carbon dioxide, other key GHGs such as methane will require people's attention in order to achieve a 1.5 °C warming scenario. In the past 20 years, global methane emissions have increased by 10% [4]. Although, compared to carbon dioxide, methane has a lower concentration [5] and a shorter atmospheric lifetime [6], the 20-year global warming potential of methane is 85 times that of carbon dioxide [7]. Therefore, scientists call on all countries to take necessary measures to control methane emissions in order to better deal with global warming [8]. The USA and the European Union took the lead in cooperation and led a Global Methane Pledge—more than 100 countries will reduce total methane emissions by at least 30% by 2030 compared with 2020 [9, 10]. As one of the main sources of methane emissions [5], the natural gas industry needs special attention in reducing emissions. In 2020, the top five natural gas–producing countries in the world were the USA, Russia, China, Iran, and Canada [11]. China's economy has developed rapidly in recent years.

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Its GDP in 2020 was second only to the USA, but far higher than Canada's [12]. However, China is the top emitter of methane, with higher emissions and a different structure of energy-related emissions compared to the USA and Canada. There is a rich body of literature on methane emissions in the USA and Canada, and the results show that field measurement results of methane emissions from natural gas are generally higher than the data published in national greenhouse gas emission inventories [5, 13]. If the methane emissions in the natural gas industry are not well characterized, this will inhibit national GHG mitigation strategies and regulations. Unfortunately, there are few studies assessing methane emissions in China's natural gas industry relative to the USA and Canada, due to differences in natural gas resource endowment and the accounting methods for methane emissions [14, 15]. Recently, the IPCC Sixth Assessment Report (AR6) was released, highlighting the need for methane emission reduction and showing that methane emission reduction in the oil and gas industry is the fastest and most economical mitigation measure [16]. This paper aims to review and summarize the limited studies on methane emissions from China's fossil fuel industry from a comparative perspective, to provide readers with a comprehensive understanding of the challenges and opportunities for methane mitigation to achieve climate and sustainability goals.

Conceptual Framework

Methane emissions from natural gas systems can generally be divided into three categories: vented emissions, fugitive emissions, and incomplete combustion emissions [17]. Among these, vented emissions are intentionally released, and fugitive emissions are unintentionally released from equipment [18]. Incomplete combustion emissions refer to fuel contained in waste gas from natural gas combustion [17]. These methane emissions occur in all phases of the natural gas supply chain, including production, processing, transmission, and distribution.

In addition, specific phases have specific quantitative methods for estimating emissions. In the production, gathering, and processing phase, the Gaussian dispersion method [17, 19] and Monte Carlo simulation [17, 20] can be used. That is, the methane concentration in the selected study area is first determined, then plugged in to a dispersion model or random model to estimate the methane leakage rate [19, 20]. When the methane leakage rate is known, it can also be combined with activity data, and then Monte Carlo iteration can be carried out to estimate the methane emissions [21]. For the transmission and distribution phase, emissions can be measured directly at the component level [17]. According to the final calculation results, the proportion of methane emissions by phase in China, the USA, and Canada are different: the USA and Canada have the largest proportion of methane emissions in the production phase [22, 23], while China has the highest proportion in the distribution phase [24]. Emission quantification methods for each phase are summarized in Fig. 1. China, the USA, and Canada also differ in total methane emissions and methane emission quantification approaches. The fundamental reason for these differences is that the energy consumption structure of these countries is different. Therefore, the study of methane emissions in the natural gas industry needs to start with energy structure as it relates to tradeoffs between gas and other energy sources, such as coal.

If it is to be a bridge fuel for energy transition, natural gas must have minimal emissions. Therefore, based on research on the current state of methane emissions and methane emission quantification, this paper discusses the methane emission reduction potential of the natural gas industry from both policy and technology perspectives.

International Comparison

Studies cited in this paper are mainly from the databases of ScienceDirect, Springer, Taylor & Francis, and Google Scholar. We focused on 210 key studies, including 60 papers about the USA, 55 about Canada, and 35 related to China, with the rest involving policy briefs, reports, etc. Eighty-nine representative and most recent references are cited in this review paper. Compared to the USA and Canada, China has much less research on methane emissions from the natural gas industry. Therefore, we try to answer the following three questions to fill this gap from a comparative perspective: first, what is the methane emission situation in China's natural gas industry? Second, what is the current research progress on natural gas methane emissions in China? Finally, what are the relevant efforts to mitigate methane emissions in China, including policies and technologies? This study tries to use the most recent research and evidence to provide the audience with answers to these questions.

First, the proportion of methane emissions from the natural gas industry out of total methane emissions is higher in the USA and Canada than in China. According to relevant research, in 2019, the methane emissions of the US oil and gas industry accounted for 30% of total methane emissions [22], of which about 74% comes from the production, gathering, and processing of natural gas [22]. In 2018, 43% of Canada's total methane emissions came from the oil and gas industry [25]. In 2014, 89.40% of China's methane emissions came from fugitive emissions, of which oil and gas systems only accounted for 5.10% of the total fugitive emissions [26].

The main reason for these differences is that the overall proportion of methane emissions from the oil and gas industry is restricted by the national energy structure. In 2020, the

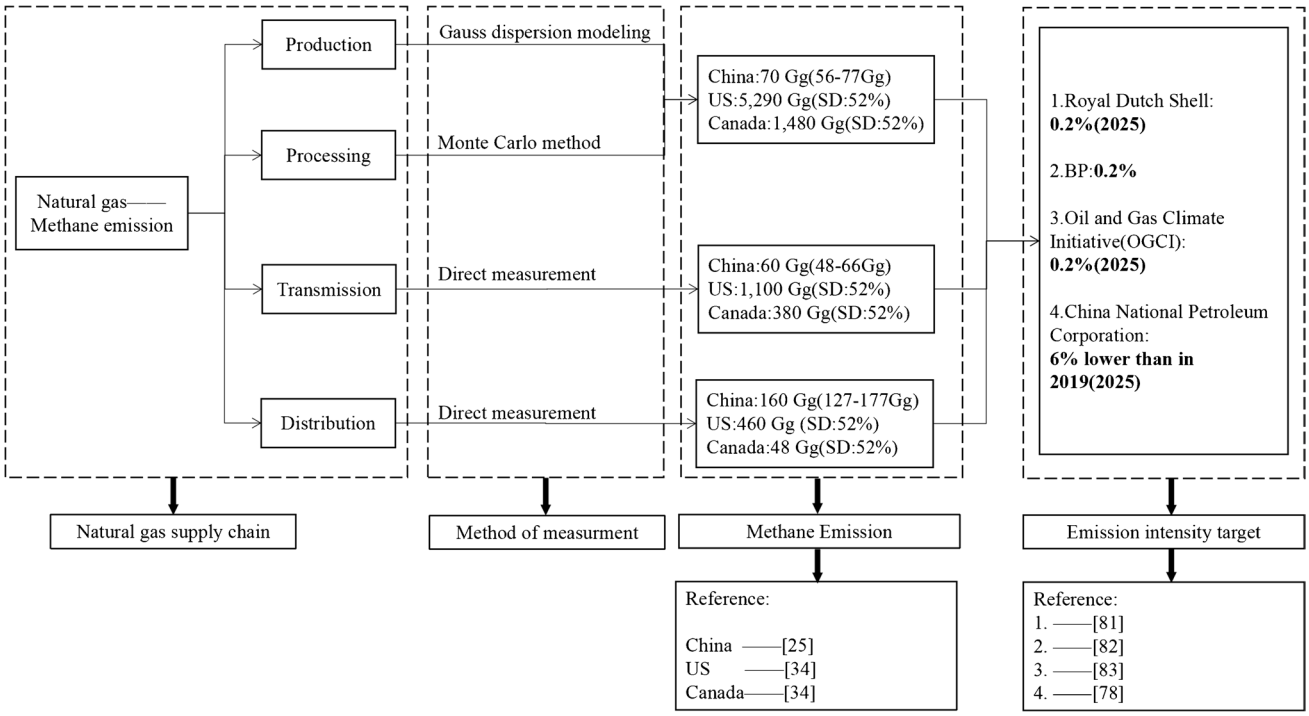

Fig. 1 Framework of methane emissions and quantification methods in natural gas systems

proportion of natural gas consumption in primary energy consumption in the USA and Canada was 34.12% and 29.71% [11], respectively. China is a coal-dominant country, with coal representing the highest proportion of any fuel in primary energy consumption, at about 56.56%, while the proportion of natural gas consumption is only 8.20% [11]. As a result, compared with the USA and Canada, the proportion of methane emissions from China's natural gas industry is relatively small. However, due to the large amount of coal consumption and production in China and the lack of effective utilization of coalbed methane, coal mining has become the largest methane emission source in China. In 2014, the methane emission from coal mines in China was 21,010 kt, accounting for 38% of total methane emissions in China [27]. In 2016, China's coal mine methane emissions increased to 22,690 kt, of which underground mining, post-mine activities, open-pit mining, and abandoned mines accounted for 83%, 13%, 3%, and 1% respectively [28]. In contrast, the total methane emissions from coal mines in the USA and Canada are much smaller than those in China, but the proportion of methane emissions from abandoned coal mines is larger than that in China. In 2019, the methane emission from coal mines in the USA was 1895 kt (abandoned coal mines accounted for 12.50%) [22], and the fugitive emission from coal mines in Canada was 56 kt (abandoned coal mines accounted for 4.30%) [29]. Therefore, the methane emissions from abandoned coal mines cannot be ignored. Some scholars have estimated the methane emissions from abandoned coal mines around the world by setting emission reduction scenarios with different intensities [30]. The results show that compared to 2010 (when the emissions from abandoned coal mines accounted for 17% of the total methane produced by coal mining), the share of abandoned coal mine emissions will increase in all scenarios in the future [30]. Therefore, compared with the USA and Canada, China's coal mine methane emission problem is more serious than emissions from the natural gas system. Especially after the introduction of China's coal cap policy [31, 32], the problem of methane emissions will become relatively more serious. On one hand, the abandoned coal mines will increase methane emissions; on the other hand, with natural gas replacing coal as an energy source, there will likely be more methane problems from gas in China in the future. Therefore, the relative amount of methane emissions in the natural gas industry is highly related to other methane emission sources like coal mining. Thus, to have a better understanding of the full picture, the energy structure and fuel replacement scenarios in China should be further studied, in addition to the main methane emission processes.

Secondly, in the natural gas industry in China, the USA, and Canada, the methane emissions from each phase are also very different. Figure 1 contains a detailed comparison of emissions from different phases of natural gas systems in China, the USA, and Canada in recent years. These data are obtained by high-resolution inversion using atmospheric methane observations [24, 33], and the standard deviation

and uncertainty range of the results are in brackets. Although this improves the estimation of methane emissions to some extent, this method is vulnerable to the accuracy of emission inventory data [33]. Data for China, the USA, and Canada for all phases of the natural gas supply chain are taken from two studies [24, 33]. These data are easily affected by the objective difference in approaches to methane quantification in each country, and the subjective factors chosen in the study. Therefore, when comparing methane emissions between countries, we consider the range of error and uncertainty. Obviously, from the perspective of emission structure, methane emissions from the USA and Canada are mainly concentrated in the production and processing phase, while China is dominated by the distribution phase. In terms of emission values, the emissions of the USA and Canada in the production and processing phase and transmission phase are much larger than those of China. The reason for this difference may be that the production and consumption structure of natural gas and the basic situation of pipelines are different across these countries. First, the inversion analysis of China, the USA, and Canada is based on the national emission inventories from before 2016 [24, 33]. Before 2016, China's natural gas production was lower than that of the USA and Canada [11]. Moreover, in 2012, the proportion of shale gas in total natural gas production in the USA and Canada reached 39% and 15%, respectively, but less than 1% in China [34]. Due to hydraulic fracturing and other reasons, the methane emissions from shale gas production are at least 30% higher than for traditional natural gas [35]. Therefore, the USA and Canada emit more methane in the production and processing phase than China. Second, gas pipelines in the USA and Canada are much longer and older than those in China. The length of gas transmission pipelines in the USA reached 500,000 km in 2007, and 100,000 km in Canada in 2014 [23], while the total length of long-distance pipelines in China was only 77,000 km in 2017 [36]. Longer transmission pipelines require more compressor stations [23]. The compressor station is the main cause of methane emissions in the transmission phase [22]. Therefore, the USA and Canada emit more methane during the transmission phase. Third, compared to the USA and Canada, China's natural gas is more dependent on imports. Forty-two percent of China's natural gas needs to be imported, including from countries like Turkmenistan, which has very high emissions per unit of natural gas production [24]. Therefore, China's high methane emission in the distribution phase is likely to be affected by international trade. In short, there are large methane emissions in the natural gas supply chain. This means that companies and countries will face serious challenges in meeting their methane emission intensity targets.

The difference between methane emissions in each phase is due to the differences in emission sources. Methane emissions during production mainly come from leakage of pneumatic controllers and equipment [37]. The main discharge source in the processing phase is the compressor [22]. Leakage of methane from the compressor station and exhaust from the pneumatic controller are the main causes of emissions during transmission [22]. Methane emissions during distribution are of high risk of leakage [15, 17]. Special attention should also be paid to the problem of pipeline leakage during this phase, which depends on the age and material of the pipeline: the leakage rate of older cast iron pipes is the highest [38, 39]. This will not only cause waste of resources and environmental pollution, but also endanger the safety of human life and property. Natural gas pipeline accidents in the USA alone cause 17 deaths and $133 million in property losses every year [40]. Therefore, it is very important to strengthen emission detection for old pipelines and gradually replace them with protected steel pipes and plastic pipelines to solve the problem. The USA took the lead in such efforts: by the end of 2020, about 97% of natural gas transmission pipelines were made of plastic or steel, and iron pipes accounted for only 3% [41]. However, methane leakage is not only related to the age and material of the pipeline, but is also positively correlated to the operating pressure of the pipeline [39]. Therefore, given the increasing demand for natural gas, solving the relationship between methane leakage and pipeline operation pressure is an important issue in the future of the distribution phase.

Methane Emission Measurement and Estimation Methodologies

In order to quantify the methane emissions in natural gas production and transmission, scholars have conducted many exploratory studies [15, 21, 37, 39]. Generally speaking, the main research methods at present include atmospheric observation methods [42–45], emission factor estimation methods [15, 46], Monte Carlo simulation methods [17, 20, 21], F.E.M.S leakage management software calculation methods [45, 47], and field detection [15, 18, 37, 39]. The calculation methods for methane emissions can be divided into two categories according to the top-down method and bottom-up method, or three categories according to Tier 1, Tier 2, and Tier 3. Among these, the top-down method refers to estimating emissions within the region. The bottom-up approach is used to estimate methane emissions from specific sectors, facilities, etc. For the three-tier system, both Tier 1 and Tier 2 quantify methane emissions based on emission factors. The difference is that Tier 1 adopts IPCC factors and Tier 2 adopts region-specific emission factors. Tier 3 is the most accurate method for measuring methane emissions in the field. Tier 1 and Tier 2 can be classified as "bottom-up" methods. Tier 3 includes both "top-down" methods such as

"aircraft mass balance method" and "bottom-up" methods such as "point-to-point detection."

Tier 1 is widely used in China. Most relevant greenhouse gas reports and scholarship are based on this method [15, 48, 49]. The emission factor method is also widely used in the national greenhouse gas inventories of the USA and Canada, but Canada has added an additional reference to Tier 3 to make the reporting data more accurate [50]. Although the emission factor method is the earliest and most basic method, more and more studies have proved that the estimation results cannot accurately represent the actual value. The progress of production technology (such as the widespread application of hydraulic fracturing and horizontal drilling) [19, 37] and the incompleteness of emission factor and activity data [51] all make the results underestimate the actual values [13, 52]. However, some scholars argue that the method overestimates the actual value [53]. It could be that the results of an emission factor model do not consider intermittent emissions [20]. Therefore, there is a certain lack of accuracy in the method of estimating methane emissions using emission factors. Research should be expanded to Tier 2 and Tier 3 levels to obtain more accurate measurement results.

At present, studies in the USA and Canada mainly use the top-down method in Tier 3 [18, 38, 54]. They use aircraft measurement [25, 37, 54], remote sensing technology [44, 45], and vehicles equipped with measuring instruments to measure methane emissions [38]. Based on these measurements, proportion-based gas concentration technologies are used to attribute the measured methane emission data to the relevant sources from the natural gas system [50, 53]. Among these, the most widely used analysis methods include the aircraft mass balance method [25, 42, 43, 54] and the remote sensing observation method [44, 45]. Researchers also use satellite data to determine methane emissions from different sectors in the Bayesian reverse modeling framework [55, 56]. China's research methods are completely opposite to that of the USA and Canada, mainly using bottom-up methods such as the Tier 1 and Tier 2 methods [57]. In addition, the research sites have been mainly concentrated in single oil and gas fields in Sichuan and Chongqing [14, 47, 53]. In particular, there are three main types of research methods applied within Tier 2; the first type is the formula method—that is, the field data is substituted into a specific formula to measure the methane emissions in some phases [58]; the second is the experimental method, which determines the methane emissions of the specific phase by simulating different external conditions [53]; the third is the model method, which can study the methane emissions of natural gas pipelines by establishing a small hole model [59]. Tier 3 is rarely used in China. In the early stages of methane emission estimation, Tier 3 approaches used the "point-to-point detection" in the bottom-up method. That is, a methane leakage detector is used to detect the leakage of different components [47] [53]. Now, a few studies have begun to expand to top-down methods with the help of satellite observations [24]. The representative research methods are shown in Table 1.

There may be several main reasons for the differences in research methods between China, the USA, and Canada. Firstly, the natural gas industry is not the main methane emission source in China, so the number of relevant studies is small and relatively recent. Moreover, the early relevant research in China was mainly to detect leakage points in the

Table 1 Representative methods for methane quantification

		Method	Introduce	References
Tier 1	Bottom-up	Emission factor	IPCC emission factor * activity data	[49]
Tier 2	Bottom-up	Emission factor	Emission factor * activity data with regional characteristics	[57]
	Bottom-up	Static calculation	Set up calculation formulas by phase and sum up, and then aggregate them to the regional case for calculation (for gas stations)	[58]
	Bottom-up	Experimental	Collect samples and simulate the methane emission rate in the laboratory according to the actual conditions. (for oilfield water)	[53]
	Bottom-up	Historical data deduction	Collect the historical data of specific gas fields and calculate the methane emissions at this stage in combination with gas composition, number of new gas wells and equipment	[53]
	Bottom-up	Small hole model	Use numerical simulation of two-dimensional turbulence to calculate (for pipes)	[59]
Tier 3	Top-down	Aircraft mass balance method	Use methane enhancement between downwind and upwind sample zones to calculate the total methane flux and emission rate	[54]
	Top-down	Remote sensing observation method	Collect methane concentration in the study area by satellite, and calculate the methane emissions by the mass balance method	[44]
	Top-down	Inversion method	Using the spatial data captured by satellites, methane emissions are estimated via the Bayesian reverse modeling framework	[24]
	Bottom-up	Field detection	Obtain emission data via methane emission detector	[47]

natural gas transmission system. Therefore, the research sites were mainly Sichuan and Chongqing gas fields because their pipeline pinhole crack occurrence rate is high, at 54% [50]. Secondly, due to the limitation of technologies in China, detection could not be completed by means of aircraft and remote sensing, so it mostly relied on manual estimation methods. Therefore, for future research, far more research on methane is needed at the national level in China.

Potential for Methane Emission Reduction

The International Energy Agency (IEA) has indicated that it is feasible to reduce global methane emissions from the oil and gas industry by 75%, and 2/3 of emission reductions can be achieved at zero net cost in developing countries in Asia [60], by selling recovered methane to pay for emission reductions. Therefore, as long as emission reduction measures are in place, the lower emission potential of natural gas can be realized. This finding gives countries and enterprises an incentive to reduce methane emissions.

In the field of methane emission reduction in the oil and gas industry, the USA and Canada are at the forefront of the world. The USA has taken steps to implement policies to control methane emissions from the upstream, midstream, and downstream segments of the oil and gas industry, and put forward requirements for oil and gas enterprises to adopt leak detection and repair (LDAR) technology in 2016 (as shown in Table 2). In addition, the Biden administration will set up new regulatory measures for the oil and gas industry to more strictly control methane emissions. Canada's efforts in methane emission reduction have also been gradually strengthened. In 2017, it proposed methane emission reduction targets through legislation, and made specific requirements for methane emission reduction technologies including LDAR, green well completion, and replacement of pneumatic devices (as shown in Table 1). In addition, it also actively provides financing for methane emission reduction in the oil and gas sector at home [64]. China's emphasis on methane emissions has also gradually increased. Since the Eleventh Five-Year Plan, policies related to methane emission control have been enacted (as shown in Table 1). Initially, these policies mainly regulated coal mining, including increasing the intensity of coalbed methane exploration and improving the utilization rate of coalbed methane. Since China made the commitment to peak emissions by 2030 and be carbon neutral by 2060, China's climate policy has entered a new stage. In the Fourteenth Five-Year Plan released in 2021, China included methane in the greenhouse gas control objectives for the first time, indicating that the Chinese government has put methane emission reduction on the agenda.

In the new stage of addressing climate change, oil and gas enterprises tend to be more willing to adopt methane emission controls. In the USA, oil and gas companies voluntarily adopted emission reduction technologies to control methane emissions [68]. This relationship then developed into the natural gas Star program, which promoted the sharing of methane emission reduction technical information throughout the industry and avoided methane emissions of more than 526 MMT CO_{2e} [69]. These emission reductions were mainly achieved by expanding LDAR [70] and replacing high-exhaust equipment [71]. Chinese oil and gas enterprises have also established a foundation in methane emission reduction, and have made great breakthroughs in recent years. The oil and gas enterprises built a light hydrocarbon recovery system [72] in

Table 2 Methane emission control policies in the USA, Canada, and China

Country	Policy	Year	Key content	Reference
USA	New Source Performance Standards (NSPS) for VOC and methane emissions from the oil and gas sector	2016	Supervise methane emissions in the upstream, midstream, and downstream segments of the oil and gas industry	[61]
	CLEAN Future Act	2021	EPA is required to formulate laws and regulations regulating all phases of the oil and gas industry before 2023	[62]
Canada	Regulations on reduction in the release of methane and certain volatile organic compounds (upstream oil and gas sector)	2017	LDAR is done three times a year; Green completion of gas wells by 2020	[63]
	Emission Reduction Fund	2020	$750 million to reduce methane emissions in the oil and gas sector	[64]
China	Some opinions on accelerating the extraction and utilization of coalbed methane (coal mine gas)	2006	Guidance of the State Council on strengthening the utilization of coalbed methane and the control of coal mine gas	[65]
	Twelfth Five-Year Plan for development and utilization of coalbed methane (coal mine gas)	2011	A target of 16 billion cubic meters of coal bed methane surface development by 2015 has been set	[66]
	Fourteenth Five-Year Plan and outline of long-term objectives for 2035	2021	Putting methane under greenhouse gas control policies	[67]

1992, and then used airtight seal detection technology to deal with the emissions from oil casings in the process of oilfield production [73]. In recent years, oil and gas companies have achieved more methane emission reduction by carrying out LDAR pilot programs [74] and enhancing natural gas recovery [75]. In addition, in order to further promote the process of methane emission reduction, China's domestic oil and gas enterprises have jointly established the methane emission control alliance, which strives to reduce the average emission intensity of methane in the process of natural gas production to less than 0.25% by 2025 [76]. At the same time, as shown in Fig. 1, foreign enterprises have also set certain targets for future methane emission intensity (the basic goal is to reduce the methane emission intensity to 0.2% by 2025) [77–79]. Thus, enterprises' awareness of methane emission reduction measures has gradually increased.

Although countries have made significant efforts to reduce methane emissions, there are still some areas for improvement. In the USA, methane regulation has been closely tied to political shifts. The Trump administration rolled back regulations on methane emissions from the production and processing phases, which hindered the deployment of new emission reduction technologies [80]. In addition, the USA has thus far failed to mitigate methane emissions from pneumatic devices, flares, etc. [81]. The Biden government has made steps towards improving methane emission regulation, but legislation is difficult to pass given the partisanship of climate-related policies in the US Congress. China is actively promoting the formation of a methane emission control system, but the current policy has not made specific requirements for emission reduction technology. This may limit the efficiency of methane emission reduction to a certain extent. In addition, some emission reduction technologies in China are still in the pilot stage, especially LDAR. At present, China mainly relies on handheld leakage detection methods [82, 83], supplemented by truck patrols [83], which require more labor and will greatly increase mitigation costs. In order to ensure that domestic enterprises successfully achieve the goal of methane emission intensity control, it is necessary for China to adopt low-cost LDAR. Therefore, while improving the methane emission control policy system, China should further encourage market mechanisms and jointly establish a number of methane emission reduction demonstration projects with enterprises, especially with regard to deploying advanced leakage detection technology.

Main Challenges and Future Prospects

Methane emissions in the natural gas industry are a problem that cannot be ignored. On the whole, China, the USA, and Canada have different methane emission profiles in all phases of the natural gas supply chain. This is closely related to the energy consumption structure of each country and methane emission sources. In terms of emission quantification methods, China mainly uses Tier 1 and Tier 2 to quantify methane emissions [48, 57–59]. There are relatively few studies using Tier 3 [47, 53], and the research has mainly been concentrated in specific oil and gas fields in Sichuan and Chongqing [14, 47]. However, studies in the USA and Canada have focused on the Tier 3 level [18, 38, 54]. More and more methane emissions are measured by aircraft, remote sensing, or vehicles equipped with measuring instruments [25, 38, 42–45]. The driving reason for the different emission levels and associated quantification processes is the difference in energy structure between countries.

As a coal-dominated country, China's coal mines represent the largest source of domestic methane emissions [15, 48]. In 2014, methane emissions from coal mines in China accounted for 38% of the total methane emissions in China [27], much larger than those in the USA and Canada. With the "coal-to-gas" policy promotion [84, 85], natural gas is expected to play an important role in China's coal replacement process, at least as an important bridge fuel to renewables in the short- and medium-term in China. The methane emissions from the natural gas industry should draw more attention than before. Motivated by this gap, this paper has compared and analyzed the challenges and opportunities faced by China in methane emission control.

Firstly, with a future increase in natural gas consumption, methane emissions from production and transmission in China deserve further attention from researchers. Since most studies are focused on a single gas mine or a single region in China [14, 47], studies conducted at the national level will be an important reference for achieving China's climate objectives. Previous research on methane emissions in the production phase was mainly completed with the help of handheld leakage detectors [14, 45, 47]. This method is relatively simple, and future research can be expanded in the direction of diversification of detection technology. In addition, there are limitations in studies at the Tier 2 level. The research sites only included gas transmission pipelines [59] and liquefied natural gas (LNG) filling stations [58]. Therefore, in the future, the research scope can be expanded through innovative modeling methods, and a list of methane emission factors suitable for China's national conditions can be established according to research data.

Secondly, facing the huge pressure of reducing the impacts of climate change, the world must make a breakthrough in methane emission reduction technology as soon as possible. Because it has the highest methane emissions from natural gas production, China can take the lead in achieving technological breakthroughs for methane emission reduction in the production phase. For the transmission phase, China can further expand leakage detection

technology. However, China is currently limited to short-range detection. Therefore, the joint development of multi-disciplinary methane quantification technology will become the focus of future studies and an area where major gas-producing and consuming countries can work together.

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Declarations

Conflict of Interest All authors declare that there is no conflict of interest.

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