



An improved method for estimating GHG emissions from onshore oil and gas exploration and development in China



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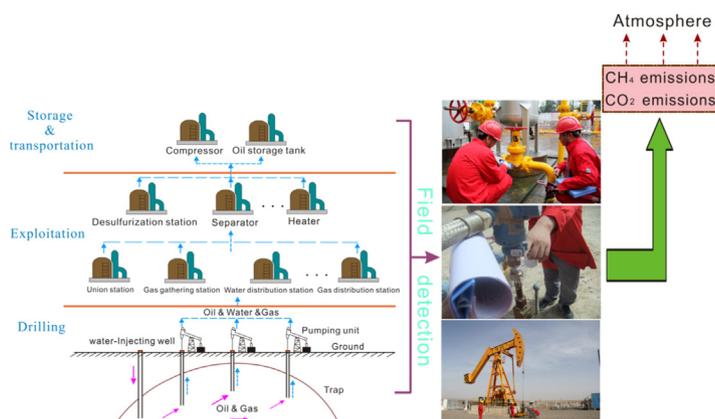
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HIGHLIGHTS

- Present a first effort to systematically measure GHG emissions from ONG exploration and development in China;
- An improved method is proposed to estimate GHG emissions from ONG systems;
- The GHG emissions of ONG systems in China were seriously overrated by IPCC method.

GRAPHICAL ABSTRACT



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ABSTRACT

Greenhouse gas (GHG) emissions from oil and gas exploration and development are major contributors to emission inventories in oil and natural gas (ONG) systems. For the developing countries, including China, studies of this aspect of the industry, being at an early stage, lack a unified method of calculation, and this leads to varied projections of national emissions. In this paper, progress is reported on direct measurement of CH₄ and CO₂ emissions along the oil and gas value chain, for four oil and gas fields. An improved calculation method (classification calculation method), which considers the production status of each type of oil and gas field in China, is proposed for the first time in this study. Based on in situ measurement, it is used to estimate the national CH₄ and CO₂ emissions from the process of petroleum exploration and development. The results showed that CH₄ and CO₂ emissions in 2013 were 73.29×10^4 and 20.32×10^4 tonnes, respectively (in CO₂ equivalent: 1559.36×10^4 tonnes). Compared with the results (731.52×10^4 tonnes of CH₄, 1031.55×10^4 tonnes of CO₂, $16,393.48 \times 10^4$ tonnes of CO₂ equivalent) in 2013 determined by the Tier 1 method of the Intergovernmental Panel on Climate Change (IPCC), the carbon emissions from field measurement method were much lower than that of IPCC method, which indicated that carbon emissions of ONG systems in China were severely overrated by IPCC. Hence, the GHG emission results reported herein could fundamentally improve the knowledge and understanding of GHG emissions from ONG exploration and development in China.

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1. Introduction

At present, global warming is considered one of the biggest environmental problems (Glagolev et al., 2008; Jeon et al., 2010; Steffen et al., 2015; Xu et al., 1999). The gases contributing most to the greenhouse effect are CO₂ and CH₄ (Amjad et al., 2011), accounting for approximately 60% and 15–20% of global greenhouse effect (Houghton et al., 1992; Rodhe, 1990; Shindell et al., 2009). CO₂ concentrations in the atmosphere increased from 370 to 392 ppm over the period 2000–2011 (Harsono et al., 2013), while global CO₂ emissions reached 34,475.64 MMT in 2010 (WRI, 2014), CH₄ concentrations increased from 1.52 to 1.81 ppm during 1978–2012 (WMO, 2012) and global CH₄ emissions reached 7195.56 MMT CO₂eq in 2010 (WRI, 2014). Despite the comparatively low concentration of CH₄ as compared to CO₂ in the atmosphere, its global warming potential (GWP) is 25 times that of CO₂ given a 100-year time horizon (Griggs and Noguera, 2002; IEA, 2008). The International Panel on Climate Change (IPCC) reports have demonstrated that the global mean sea level has risen by 0.19 m over the period 1901–2010 and the global average temperature increased by 0.85 °C over the interval 1880–2012 (IPCC, 2014). Global warming potential is expected to accelerate in the coming decades (Bradley, 2001; Hansen et al., 2002; Katyal, 2009), and Dlugokencky et al. (2011) claimed that a reduction in CH₄ emissions would rapidly benefit the global climate; thus, it is particularly imperative to investigate and reduce GHG emissions to mitigate global warming to a certain extent (Choudhary et al., 2008).

A variety of human activities (Fig. 1) can become sources of manmade GHG emission (Duxbury et al., 1993; IPCC, 2007; Yuan et al., 2012; Steffen et al., 2015). The energy supply for these activities is the second largest CH₄ emission source, accounting for 37% of the global CH₄ emissions produced by human activities (emissions of 2713.2 MtCO₂eq in 2010: EPA, 2012). Furthermore, oil and natural gas systems (ONG) are the leading CH₄ emission source in the field of energy supply, with emissions of 1677.3 MtCO₂eq in 2010 (EPA, 2012).

GHG emissions from ONG systems are projected to increase by 26% between 2010 and 2030 (EPA, 2013). The absence of systematic direct in situ measurements along infrastructures used in the process of oil and gas exploration and exploitation, limits the opportunity to evaluate GHG emission reduction strategies (Burnham et al., 2012). Clearly, there is limited understanding of GHG emissions from oil and gas exploration and exploitation facilities, including those in the United States (Howarth et al., 2011). Anifowose and Odubela (2015) presented a modest attempt to estimate CH₄ emissions from the System 2C crude oil transport pipeline in Nigeria. Allen et al. (2013) first carried out a series of studies measuring CH₄ emissions at natural gas production sites in the US. To date, there has been no similar measurement study to

gather scientific estimates, or to locate specific sites of emission in the oil and gas infrastructures in China. Presentation of carbon emissions produced by the energy activities in China is missing from the literature. Based on the IPCC method, there have been several studies of the national-scale inventories of CH₄ emissions in China's oil and natural gas industry for year 1980–2007 (Liu et al., 2008; Zhang et al., 2014). However, because of the lack of measurement data and complex & volatile emission sources in ONG systems, not all the estimates acquired essentially are well reflective of the real situation in China. Therefore, the scientific quality and accuracy of such estimates are inadequate (IPIECA, 2011; Penman et al., 2000; Zhu et al., 2015). This is because default emission factors in the IPCC method include the performance of average GHG emission levels in developing countries but do not fully reflect current situation in China's oil and gas industries, given the advancement and development of technology. Moreover, the default emission factors were applied to the whole petroleum system in IPCC method, without considering the production status of each field in China (CCCCS, 2000). Furthermore, those estimates tended to focus mainly on CH₄ emissions and to ignore CO₂ emissions.

In view of the above-mentioned facts, there is still limited estimate about the GHG emissions from ONG systems in China. The estimates in previous report still cannot reflect the actual situation. To understand and estimate the actual emission of China's ONG systems, a more accurate method, which can reflect the current situation of oil and natural gas fields in China, is urgently required.

The purpose of this paper is twofold. First, establish an emission factor (country-specific factor) which is suitable for China's ONG systems by measuring several representative oil and gas fields. Next, perform a detailed estimate of carbon emissions in China during 2010–2013. The national estimates based on field measurement are compared with those by IPCC method. This comparison could provide reliable basic data and a more scientific basis for policy making to alleviate global warming.

2. Methodology

2.1. Conventional methodology (IPCC Tier 1) for estimating GHG emissions

At present, there is no uniform calculation method for estimating the GHG emissions from oil and gas systems around the world. The Tier 1 approach (IPCC, 2006), of which the given emission factors have come to be seen as applying to all developing countries, has been widely employed to estimate GHG emissions of ONG systems in China. According to the recommendations of conventional method, where the emissions are equal to an emission factor multiplied by the corresponding activity factor along the ONG chain (category), the GHG emissions from oil and natural gas systems can be calculated as indicated in Formula 1 and Formula 2.

$$E_{gas,industry\ segment} = A_{gas,industry\ segment} \cdot EF_{gas,industry\ segment} \quad (1)$$

$$E_{gas} = \sum E_{gas,industry\ segment} \quad (2)$$

where, E_{gas} is the emission (Gg), $A_{industry\ segment}$ is the activity factor (number of new drillings, testing wells, well servicing and production wells, oil and gas production), $EF_{industry\ segment}$ is the emission factors (Gg/unit of activity), E_{gas} is the total emissions of industry segments. The exploration and development data corresponding to active factors of different categories in the IPCC method, which were used to calculate the GHG emissions of ONG systems, were collected from the statistical yearbook (CNPC, 2014; CPC, 2014).

2.2. An improved method for estimating GHG emissions

Because of the limitations of the IPCC method, an improved method (classification calculation method) that better considers the actual

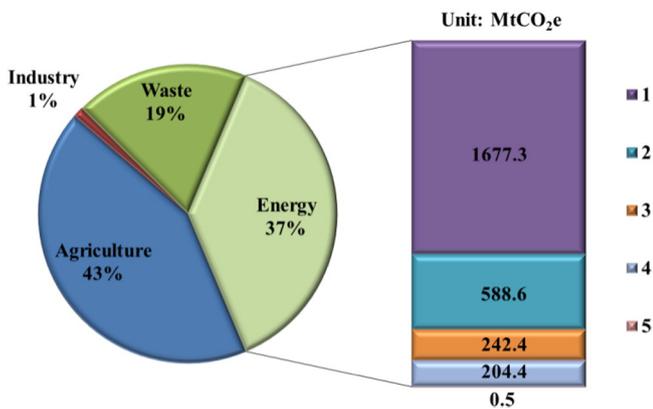


Fig. 1. Global methane emissions from energy activities in 2010, categorized by source (inlet: methane emission by sector) (EPA, 2012): 1-Natural Gas and Oil System; 2-Coal Mining Activities; 3-Stationary and Mobile Combustion; 4-Biomass Combustion; and 5-Other Energy Sources.

situation of China's petroleum system is proposed to estimate national CH₄ and CO₂ emissions from the ONG systems more accurately. This method is substantially different from that of IPCC method (regarding petroleum as a whole). The details of this method are as follows.

2.2.1. Classification of GHG emission category

The process of oil-gas exploration and development is divided into drilling, exploitation, storage, and transport according to the actual production states in ONG fields in China (API, 1999, 2001; Ritter et al., 2005) (Fig. 2). The potential sources of GHG emissions in ONG systems during exploration and development include drilling, well testing, equipment maintenance, gas production, processing, oil production and oilfield water (IPCC, 2006; Chen et al., 2014; Yang et al., 2016b). Categorization of the emission from gas processing and oil production adopted by the present authors is not consistent with that of the IPCC method (Table 1). The manufacturing plants listed in IPCC (2006) do not exist in China, and they are replaced by different facilities there (Zhong et al., 2015). Due to their demanding technology and high cost, conventional oil and heavy oil, the leading components of crude oil output in China, are treated as the focus of research of the authors. The equipment maintenance category covers all possible forms of maintenance, which is more comprehensive than the approach used in the IPCC method. Moreover, in the present study, oilfield water is considered a source of GHG emissions, owing to the natural gases dissolved in it, which is not considered in the IPCC method.

2.2.2. The selection of representative ONG fields

Special research efforts have been made to analyze and summarize the characteristics of oil-gas fields in China. The onshore oil-gas fields in China are divided into four types, based on field investigations and recovery mode used in the ONG fields. These are natural gas exploitation

Table 1
Comparison of emission category between IPCC and measurement method.

Category	Sub-category	
	IPCC method	Field measurement method
Drillings	All	All
Well testing	All	All
Equipment Maintenance	All	All
Gas production	All	Well heads, single well stations, collecting stations, gas distributions et.
Gas processing	Desulfuration plants, acid gas removal plants, refinery hydrogen plant	Extractors, desulfurization tower and superchargers et.
Oil production	Conventional oil, heavy oil, conduction oil, synthetic oil et.	Conventional oil, heavy oil
Oilfield water	No statistics	All

"All" denotes all fugitive emissions as well as venting and flaring emissions.

and transport, oil-gas concurrent production and transport, crude oil exploitation and transport and other types (Fig. 3). In total, there are 28 large oil and gas production regions in China. Based on the field investigation, the number of natural gas fields, oilfields, oil-gas concurrent production and the other type are 7, 11, 4 and 6, respectively. In this study, representative large-scale ONG fields of each type were selected as the research objects. The ratio of the production of selected ONG fields to national output is about 50%.

The Shunan gas field is located in the south of Sichuan Basin and is one of the largest production bases of natural gas in the area. The Sebei gas field is located in Qinghai Province, and is the fourth largest gas field in China. Hence, choosing the two as research objects represents the current situation of natural gas exploration and development

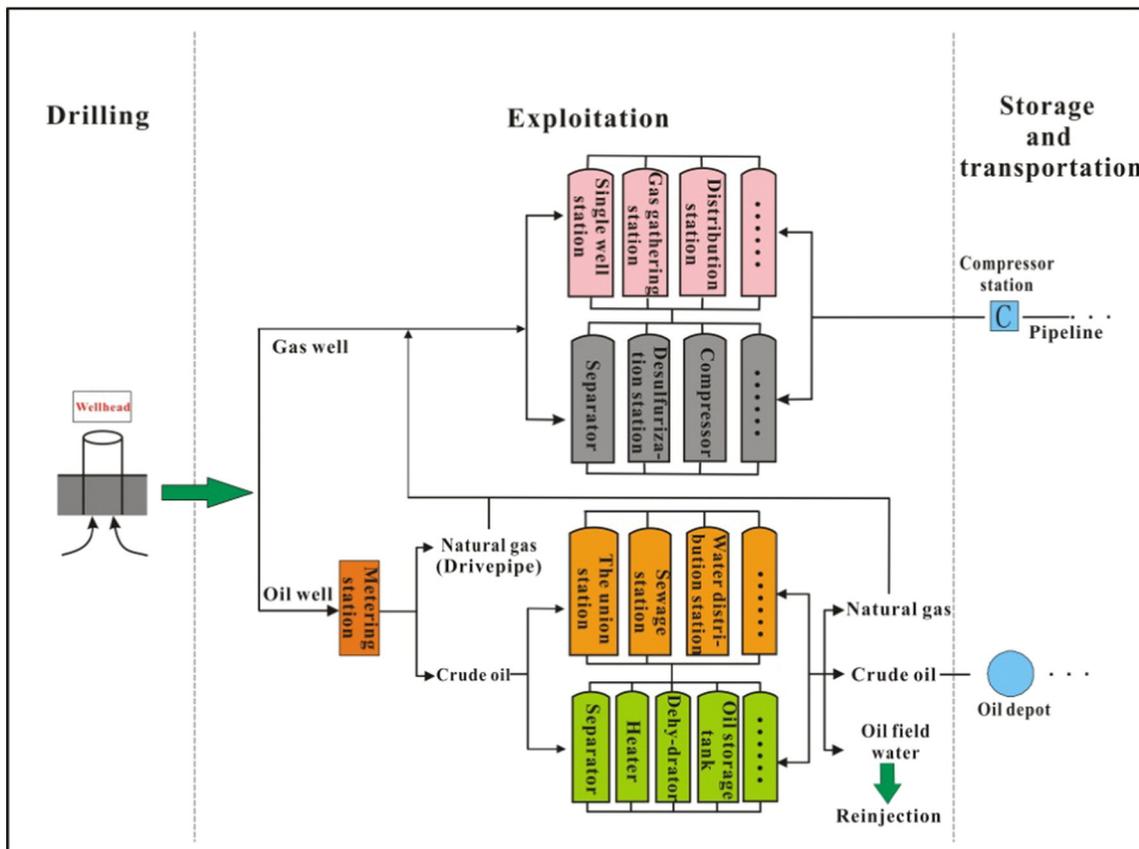


Fig. 2. Oil and natural gas development workflow.

in China. The possible categories of GHG emission sources are drilling, well testing, equipment maintenance, gas production, gas processing, and oilfield water.

The Tuha oilfield, located in the Turpan-Hami Basin (Xinjiang), is a typical (in China) oilfield with concurrent production of gas and oil. GHG emission sources during exploration and development were concentrated in well testing, gas production, gas processing and oilfield water. The specific emissions in the different categories are as follows.

The Daqing oilfield, located near Daqing City in Heilongjiang Province, is the largest oilfield in China. The emission categories of the Daqing oilfield include well testing, equipment maintenance, gas production, gas processing, oil production, and oilfield water. The leading emission source for Daqing oilfield was the release of casing gas at its wellheads. The accumulation of the associated gas at the wellhead causes an increased pressure. After the pressure reaches a certain level, the gas is released directly into the atmosphere at irregular intervals.

Field research showed that the development wells in the Dagang and Jidong oilfields are relatively scattered. The utilization ratio of associated gas is low because of the lower amount of associated gas and higher recycling costs for the remote and scattered well areas. As a consequence of this, the associated gas was released directly into atmosphere. Given this, the average initial gas-oil ratio of the two fields were collected.

2.2.3. In situ measurement of representative ONG fields

The typical ONG fields corresponding to the above 4-party classification are Shunan and Sebei gas fields, Tuha oilfield, Daqing oilfield, and the Dagang and Jidong oilfields, respectively. Field measurements and indoor simulation experiments along the ONG value chain, according to the IPCC method, were both carried out to investigate and acquire estimates of carbon emissions from exploration and development.

This work reported direct measurements of CH₄ leakage from four oil and gas fields with 52,699 detection points, all of which were randomly distributed across 145 wellheads, 16 single well stations, 28 gas gathering stations, 12 distribution stations, 17 union stations, 53 separators, 41 dehydration towers, 41 heater furnaces, 39 desulfurizing towers, 6 sewage stations, 10 compressor station, 3 light hydrocarbon factories, and 9 oil transport stations. In order to improve detection efficiency and avoid missing leakage point, soapy water was spilled onto the detection point to generally understand whether the emission exists in the first place. If it exists, then a highly-sensitive WAT-80 pump-suction-type infrared methane detector with detection limit of 1 ppm was used to detect leakage sources (e.g., flanges, valve elements, joints, fat liquoring holes) of facilities during field work in 2013, and obtained a CH₄ leakage rate in the monitoring period (30 s). Indoor simulation experiments are conducted as follows: (1) In order to accurately estimate combustion emissions, the pilot burner experiment was carried out to obtain the combustion ratio of natural gas under atmospheric conditions (SM-Fig. 1); (2) The emissions from oilfield water were simulated in an improved static flux chamber apparatus (Chen et al., 2014).

Gas samples were collected at each measurement and simulation experiment categories, and natural gas component analysis experiment was carried out using a gas chromatography combined with mass spectrometry to obtain the concentration ratios of CH₄ and CO₂. Combining the CH₄ leakage rate with the gas component data, the annual leakage of CH₄ and CO₂ at each leak-point was calculated using self-developed conversion calculation software. The auto-calculation software on the basis of Excel spreadsheet can convert the leakage in sampling time (30 s) into annual emissions just by importing the original measurement data. To avoid accidental errors of measurement data, repeated measurements were also carried out in 2013. Each potential leakage point was measured for twice each time, then took an average. The two measurements average emissions reported in this work for each

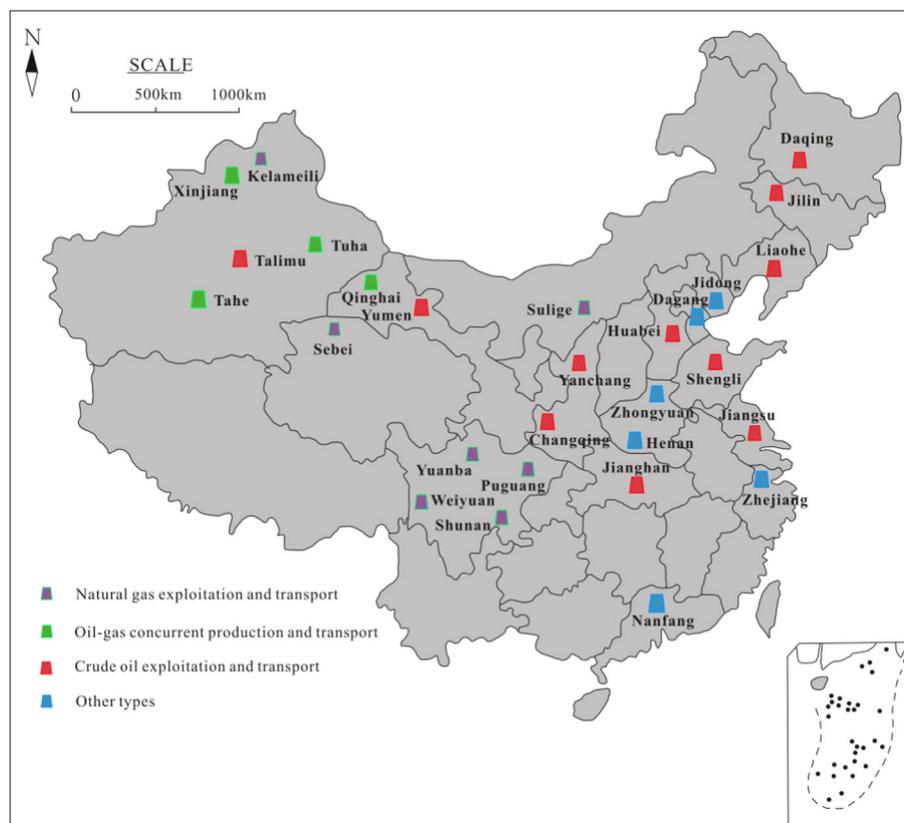


Fig. 3. Classification of onshore oil-gas fields in China.

category of typical oil and gas fields are assumed to be representative and are applied to estimate national emissions.

2.2.4. Establishment of an improved method for estimating GHG emissions

The emissions of each representative ONG field were acquired through in situ measurement and indoor simulation experiments. The comprehensive emission factor for each representative ONG field, which was regarded as a general emission factor to calculate the total emissions of corresponding types of ONG fields, were obtained by dividing total measured emissions by total output. The total emissions of each type were equal to the comprehensive emission factor multiplied by the total output of each oilfield type. The total emissions produced by exploration and development of ONG systems in China were obtained by summing up the emissions of each oil-gas field type. The improved calculation method proposed for estimating national emissions is summarized in Formula 3 and Formula 4:

$$E_{gas,i} = A_i \cdot EF_{gas,i} \quad (3)$$

$$E_{gas} = \sum E_{gas,i} \quad (4)$$

where, E_{gas} is the total emissions (tonnes) from ONG exploration and development; A is the active factor of each type of ONG field; and $EF_{gas,i}$ is the comprehensive emission factor, and i is the type of the ONG field (as classified for this study).

3. Results

3.1. Emissions calculated using IPCC Tier-1 method

Following the IPCC Tier-1 emission factor approach, the estimated CH₄ and CO₂ emissions from ONG systems in China are shown in Table 2. The emissions of CH₄ and CO₂ in 2013 were 731.52×10^4 tonnes and 1031.55×10^4 tonnes, respectively, which when converted to CO₂ equivalent, was about $16,393.48 \times 10^4$ tonnes.

3.2. Emissions calculated in measured method

3.2.1. Natural gas exploitation and transport - Shunan and Sebei gas fields

(1) GHG emissions in different categories

The field measurement results in the different categories are as follows.

Drilling: Site-test results showed zero leakages during the drilling process, which is because of improvements in drilling and blowout-prevention technologies.

Well testing: The GHG emissions from the well testing comprise three parts: (1) CO₂ produced by flaring of natural gas, (2) CO₂ within natural gas, and (3) the CH₄ remaining after incomplete combustion.

Combining the field data with component analysis data of the natural gas and the results from the simulated combustion emission experiment result (with combustion ratio of $98\% \pm 0.5$) of a pilot burner, the annual emissions of CO₂ and CH₄ were calculated out using self-developed software (SM-Table 1).

Equipment Maintenance: Equipment failure is inevitable during operations. Natural gas inside the equipment has to be emptied to carry out equipment maintenance work, which results the GHG emissions. The typical equipment maintenance cycle is 3–5 years or longer. The volumes of the production equipment in the Shunan field were collected and converted to standard volumes (SM-Table 2). Combining the natural gas component data with its volume and density, the average emissions for each gas field were obtained. The total emissions of CH₄ and CO₂ in this category were acquired using the average emission per gas field, multiplied by the total number of gas fields. The CH₄ and CO₂ emissions obtained were 811.55 tonnes, 7.8 tonnes, respectively, in Shunan; and 35.27 tonnes, and 0.04 tonnes, in Sebei.

Gas production and gas processing: There are no flaring and venting emissions listed by the IPCC method in these two gas fields. The main emission source for the two was facility leakage. Thus, the same in situ measurement method was used to calculate and acquire GHG emissions in the two categories. The valve elements, joints, flanges, fatliquoring holes, and orifice fittings, distributed in seven areas (well heads, separators, gas terminal stations, single well stations, gas distributions, compressors) were tested (with check points 11,022 and 17,979 corresponding to Shunan and Sebei, respectively). Combining the leak data acquired from field measurement and the total number of facilities, emissions in this category were obtained (SM-Table 3).

Oilfield water: Dissolved CH₄ and CO₂ release from the oilfield-produced water with an abrupt decrease in temperature and pressure. The water samples from the two gas fields were collected directly from drainpipe after the three-phase separation by an oil-gas water separator before they reached the well. In-field investigation showed that the oilfield water of research area was recycled within 72 h. Emissions from oilfield-produced water under 5, 15 and 30 °C were simulated within 0–72 h (SM-Table 4). By multiplying the emission rate for the local annual average temperature of 15 °C in Shunan, with annual oilfield water production (187.01×10^4 m³), the CH₄ and CO₂ emissions were 26.01 and 61.11 tonnes, respectively. The emissions of CH₄ and CO₂ from Sebei were 2.98 and 6.0 tonnes, respectively, by multiplying the emission rate at the local annual average temperature of 5 °C by the annual oilfield water production volume (23.35×10^4 m³).

(2) Establishment of a comprehensive emission factor

The comprehensive emission factor was calculated by dividing the total emissions by corresponding production data of the gas field. The general emission factor of natural gas gathering and transport was taken as the mean of the two measured emissions (SM-Table 5).

Table 2
GHG emissions calculated by IPCC method in 2013.

Category	Emission source	Emission factor		Active factor	Emission/ton		
		CH ₄	CO ₂		CH ₄	CO ₂	CO ₂ -eq
Well drilling	Flaring and venting	2.97E-04	9.00E-04	21,423	6363	19,281	152,896
Well testing	Flaring and venting	4.51E-04	7.95E-02	1746	787	138,807	155,343
Well servicing	Flaring and venting	9.55E-04	1.70E-05	203,321	194,172	3456	4,081,059
Gas production/10 ⁴ m ³	Fugitives	1.22E-02	9.70E-05	9,988,300	1,218,573	9689	25,599,713
	Flaring	8.80E-07	1.40E-03	9,988,300	88	139,836	141,682
Gas processing	Fugitives	2.50E-04	2.00E-05	9,988,300	24,971	1998	526,383
	Flaring	2.40E-06	3.55E-03	9,988,300	240	354,585	359,619
Oil production/tonne	Fugitives(onshore)	3.00E-02	2.15E-03	167,750,000	5,701,906	408,637	120,148,666
	Venting	8.55E-04	1.13E-04	167,750,000	162,500	21,382	3,433,887
	Flaring	2.95E-05	4.85E-02	167,750,000	5607	9,217,851	9,335,593
Total					7,315,206	10,315,521	163,934,841

3.2.2. Oil-gas concurrent production and transport–Tuha oilfield

(1) GHG emissions in different categories.

Well testing: The well testing mainly targeted new wells. The number of new wells drilled in the oilfield was 39 in 2013. The daily average natural gas emissions per well tested were about 2169 m³, with well-testing duration of about ten days. The total natural gas emission in this category was about 84.59×10^4 m³ annually. Emissions of CO₂ and CH₄ were calculated by combining the natural gas component data and pilot-burner experiment results (SM–Table 6).

Gas production: Investigations indicated that the main emission sources in this category were fugitive and flaring. The fugitive sources include joints, valve elements of various facilities located in wellheads, gas-gathering stations, etc. The field-measured leakage data from a handheld concentration detector are shown in SM–Table 7. Flare emissions were concentrated at the gas-gathering stations. The daily amount of natural gas burned at each gas-gathering station was about 100 m³, and that caused by equipment failure was about 1393 m³. Average number of equipment failure for each gas-gathering station was about 10 times a year with duration of 7 days each time. Seven gas-gathering stations in Tuha oilfield release 35.30×10^4 m³ natural gas. Combining the natural gas component data and burning rate with the total natural gas amount, the emissions of CO₂ and CH₄ were obtained (SM–Table 8).

Gas processing: Fugitive and Flaring were also the main GHG emission sources in this category. The fugitive emission sources were joints, valve element, the fat liquoring holes, flanges located in separators and compressors, and in the light hydrocarbon factory. The measured fugitive data was calculated and is given in SM–Table 9. The flaring emissions comprise: (a) the daily amount of natural gas burned for each light hydrocarbon factory, which was about 100 m³; (b) the amount of natural gas burned caused by equipment failure for each light hydrocarbon factory, which amounted to 2476 m³/day. The average number of equipment failures for each light hydrocarbon factory was 10-times/year. There are five light hydrocarbon factories in the Tuha oilfield. The overall emissions caused by flaring of natural gas were 30.63×10^4 m³. Combining the component analysis of natural gas and the burning rate experiment, the emissions of CO₂ and CH₄ were obtained (SM–Table 10).

Oilfield water: According to the simulated experiment results, the emission rates of CH₄ and CO₂ were 13.86 and 32.65 g/m³, respectively. Combining the oilfield water production (9.68×10^4 m³) with the emission rate, CH₄ and CO₂ emissions in this category was calculated to be 1.34 and 3.16 tonnes, respectively.

(2) Establishment of a comprehensive emission factor

Through the field monitoring and simulation study on the different categories, the total CH₄ and CO₂ emissions were 38.308 and 3660.733 tonnes, respectively. The comprehensive emission factors of CH₄ and CO₂ were obtained by dividing emissions by total crude output (SM–Table 11).

3.2.3. Crude oil exploitation and transport –Daqing oilfield

(1) GHG emissions in different categories.

Well testing: According to abundant statistic data, the average emissions of CH₄ and CO₂ were 366.98 and 2.13 tonnes per gas testing and 0.16 and 0.24 tonnes (respectively) per oil testing well. The total GHG emissions produced in the well-testing category were obtained by combining the numbers (61 gas wells and 13 oil wells) of wells tested (SM–Table 12).

Equipment maintenance: The production equipment volume in key oilfields (including Xingyuan, Xingmao, and Dumeng) was collected.

The average GHG emissions per oilfield were calculated on the basis of natural gas composition and collecting equipment volume. Combining the total number of oilfields in Daqing, the GHG emissions in this category were obtained. The emissions of CH₄ and CO₂ were 204.38 and 139.36 tonnes, respectively.

Gas production and processing: Combining the field measurements at gas gathering stations, transport stations, union stations, and water-injection stations with the natural gas composition analysis, the emissions of CH₄ and CO₂ were 64.36 and 43.89 tonnes, respectively.

Oil production: releases of casing gas at wellheads and the leakage of facilities were the main sources of emissions in this category (SM–Table 13). Through statistical analysis of 166 exploitation wells, the average venting of CH₄ and CO₂ of per well was found to be 0.89 and 4.04 tonnes, respectively. Assuming the number of wells releasing casing gas accounted for 1% of althea exploitation wells, the total amount of casing gas released was 31,565.44 tonnes CH₄ and 21,541.28 tonnes CO₂.

Oilfield water: The reinjection time for produced water was normally 12 h. The emission rates (SM–Fig. 2) of CH₄ and CO₂ released from oilfield water were 1.24 g/m³ and 13.31 g/m³, respectively. Combining the oilfield water production, with its content (33.21×10^4 m³), the total emissions of CH₄ and CO₂ in this category were 0.41 and 4.42 tonnes, respectively.

(2) Establishment of a comprehensive emission factor.

The total carbon emissions of Daqing oilfield were obtained by summing up the emissions in the different categories. The measured comprehensive emission factor was obtained by dividing the measured emissions by the total crude oil production (SM–Table 14).

3.2.4. The other types–Dagang and Jidong oilfields

Combining the average initial gas-oil ratio [71 m³ (natural gas) / tonnes (crude oil)] with the average natural gas component data (83.85% of CH₄ and 1.37% of CO₂), the comprehensive GHG emission factor was estimated based on the rule of maximum emission. The comprehensive emission factors of CH₄ and CO₂ were 4.58E + 02, 1.77E + 01, respectively.

3.2.5. National emission estimates based on the measurement method

The CH₄ and CO₂ emissions calculated by the classification calculation method based on in-situ measurement are shown in Table 3. The emissions of CH₄ and CO₂ were 73.29×10^4 and 20.32×10^4 tonnes, respectively, which convert to CO₂ equivalent of about 1559.36×10^4 tonnes.

4. Discussion

4.1. Comparison between the measurement method and the IPCC method

From the foregoing calculation results, it is obvious that the main emission categories for both methods were gas production and processing, and oil production; followed by well testing, well servicing, oilfield water, and drilling. This indicated that the results from the two methods (regarding priority of categories) had a same trend. The results calculated using the classification calculation and IPCC methods were presented in Table 4. The estimates of CH₄ and CO₂ calculated by the IPCC Tier 1 method were about 10-times and 51-times higher than that of corresponding CH₄ and CO₂ calculated by our method, respectively. The CO₂-eq by the IPCC Tier 1 method was about 11-times than that calculated by the classification calculation method.

The results calculated using the IPCC method showed that CH₄ emissions were much lower than CO₂, which indicated that flaring was the main emission source. However, the results calculated using the measurement method showed the opposite. More specifically, fugitives

Table 3
GHG emissions calculated by measurement method in 2013.

	Average measured factor		Active factor	Emission/tonne		
	CH ₄	CO ₂		CH ₄	CO ₂	CO ₂ -eq
Natural gas exploitation and transport	5.67E + 01	2.80E + 01	998.83	56,638	27,954	1,217,352
Oil-gas concurrent production and transport	2.47E – 01	2.36E + 01	2303	569	54,391	66,340
Crude oil exploitation and transport	1.11E + 01	7.54E + 00	13,321.85	148,231	100,404	3,213,253
The other type	4.58E + 02	1.77E + 01	1150.59	527,440	20,403	11,096,640
Total				732,878	203,152	15,593,580

and venting were the main emission sources during the process of on-shore ONG exploration and development in China.

The foregoing analysis showed that GHG emissions calculated for the process of oil and gas exploration and development using the IPCC method were significantly exaggerated. The main reason accounting for this was because the IPCC method did not fully consider the actual production situation (production way, advancement and development of technology etc.) of ONG fields in China, resulting in an overestimate of carbon emission. For example, flaring and venting emissions in gas production and processing categories listed in IPCC method did not exist in Shunan and Sebei gas fields. In addition, IPCC held that the fugitive emission from facilities is the leading emission source in oil production category, but the field investigation found that the leading emission originated from casing gas venting of wellheads in Daqing oilfield, and the ratio of casing gas emissions to the total emissions in Daqing reached about 71.3%. Field measured results showed that the release rate of casing gas was much lower than facilities leakage, because only when the pressure inside casing reached a certain level could the gas be released. The analyses above indicated that GHG emissions from ONG systems were overestimated by IPCC. Due to lack of measured data, it was worth discussing the applicability of emission factors proposed by IPCC for ONG systems in China. The improved calculation methodology proposed in this paper, which was obtained using large amounts of field measurements, is more specific and scientific.

4.2. Comparison of GHG emissions in China and in USA

China and USA are the top two emitters of GHG in the world. The Environmental Protection Agency (EPA, 2010) estimates that gas leaks from oil and gas sector are responsible for 29% of U.S. methane emissions. The energy-related CH₄ emissions in USA were greater than those in China before 1994, and China surpassed USA with energy consumption rapidly rising in recent years (Zhang et al., 2014). The energy-related CO₂ emissions in China increased from 2216.9 MMT in 1990 to 9023.1 MMT in 2013, and decreased in USA from 4802.5 MMT in 1990 to 5119.7 MMT in 2013, as reported in EPA (2016). This is an increase of 307.0% and 6.6%, respectively, and China's CO₂ emissions from energy activities were 1.76 times those of USA. However, if we take demographic factors into consideration, the conclusion will be very different. The per capita emissions for USA were 16,178 kg in 2013, 2.45 times that of China.

Zhang et al. (2014) presented a comparison of the emission shares for key source categories in China and in USA, and found the main emission contributors in China and in USA were coal mining and natural gas system leakage. The CH₄ emissions from oil and gas system in USA

decreased from 206.8 MMT CO₂ eq in 1990 to 175.6 MMT CO₂ eq in 2013, corresponding to 60% and 55% of the energy-related CH₄ emissions, as reported in EPA (2016). However, the measured data in this study indicated that the CH₄ leakage in China's ONG systems was 0.7329 MMT, accounting for a very small proportion of the total energy-related CH₄ emissions in 2013.

4.3. Comparison with existing studies

Scholars had attempted to estimate the GHG emission in China's ONG systems, but had not reached a unified estimate (Table 5). With CH₄ emissions from ONG systems in 2007 as an example, the values varied considerably among different studies, with the higher one being about 2.5 times higher than that of the lower value. Zhang et al. (2014) held that the oil and natural gas production showed excellent agreement with GHG emissions through statistical analysis in 1980–2007, and the rough CH₄ emission in 2010 was accordingly calculated, with estimates of 0.8263 MMT, much higher than that of our result (0.7232 MMT) in 2010. Comparing the above results with the present study, our results were not entirely consistent with previous study.

The causes of this phenomenon were that scholars took different emission factors provided by different organizations or individuals to estimate the national emission from ONG systems due to lack of unified calculation method, resulting in different estimates. The deep-rooted reason accounting for this was lacking of compelling in situ measurement data and country-specific emission factors. Hence, our method based on in situ measurement can reflect the actual emission and provide more reliable and accurate references in estimating the GHG emission from China's ONG systems.

4.4. Uncertainty in estimated CH₄ and CO₂ emissions from ONG systems

Despite efforts to enhance accuracy of field data measured in situ, uncertainties and limitations of data quality are inevitable and thus restrict national estimates. To estimate the emissions from ONG systems, uncertainty arose from measurement uncertainty, uncertainty introduced by the selection of sites, and uncertainty due to choices in performing regional equipment counts. More detection points distributed in more equipment are needed to control and reduce this uncertainty. The maintenance period of equipment is uncertainty because it depends on the production status and equipment ages. The local climatic conditions (such as wind speed) can dilute the CH₄ concentration, and result in lower field measured values, thereby increasing uncertainty. Atmospheric temperature affects GHG emissions from crude oil and

Table 4
Comparison of calculation results between measurement and IPCC methods.

Year	IPCC method/tonne			Measurement method/tonne		
	CH ₄	CO ₂	CO ₂ -eq	CH ₄	CO ₂	CO ₂ -eq
2010	6,692,597	9,920,574	150,465,109	723,229	188,042	15,375,851
2011	6,910,538	9,949,653	155,070,952	721,938	192,890	15,353,578
2012	7,119,973	10,180,555	15,969,980	725,088	197,481	15,424,327
2013	7,315,206	10,315,521	163,934,841	732,878	203,152	15,593,580

Table 5
Estimates of CH₄ emissions in China.

Methane emissions/MMT	Year	References
0.0919	1990	CCCCS (2000)
0.2249	1994	Zhang et al. (1999), INCCCC (2004)
0.626	2006	Liu et al. (2008)
0.6543	2007	Zhang et al. (2014)
0.2583	2007	Zhang and Chen (2010)

oilfield water (Chen et al., 2014, Yang et al., 2016a). Although repeated measurements were carried out to present a mean emission level, this work still could not entirely reflect the actual emissions, given the seasonal changes in temperature.

Another uncertainty in the national emission estimates originated from the mining technology difference between oil-gas fields of the same type, whose technique level cannot be fully guaranteed to be exactly same, and this can cause a certain error when the comprehensive emission factor of representative oil and gas fields was applied to calculate emission of corresponding type. The best way to reduce this uncertainty in the estimate is to increase field measurement works to cover more oil-gas fields in future research. In general, even considering the uncertainties mentioned above, the scale of CH₄ and CO₂ in ONG systems of China are unlikely to be affected significantly because basically all emission categories were contained in this investigation, and the leading emission sources were controlled and measured in field work, and the estimates presented in this paper may offer fundamental improvement in the knowledge and understanding of GHG emissions from ONG exploration and development in China. We should emphasize that enhanced dynamic monitoring and analysis of ONG systems will be essential in preparing a more detailed and more accurate national estimates.

5. Conclusions

GHG emissions from the process of oil and gas exploration and development are an important component of GHG emission inventory in oil and natural gas systems. The onshore ONG fields in China can be classified into four types: natural gas exploitation and transport, oil-gas concurrent production and transport, crude oil exploitation and transport, and other types. The comprehensive emission factors of CH₄ and CO₂ (corresponding to the four types) were 5.67E + 01 and 2.80E + 01; 2.47E – 01 and 2.36E + 01; 1.11E + 01 and 7.54E + 00; and 4.58E + 02 and 1.77E + 01, respectively. The estimated CH₄ and CO₂ emissions for each type were 56,638 and 27,954 tonnes; 569 and 54,391 tonnes; 148,231 and 100,404 tonnes; and 527,440 and 20,403 tonnes, respectively. Fugitives and venting were the main emission sources, not flaring, as indicated by the IPCC results during the process of checking ONG systems in China. The leading CH₄ emissions occurred in the field of other types, and in crude oil exploitation and transport. Based on analysis of a large amount of in situ measurement data, the total emissions obtained were 73.29 × 10⁴, 20.32 × 10⁴, 1559.36 × 10⁴ tonnes of CH₄, CO₂, and CO₂-eq, respectively. Compared with the results (731.52 × 10⁴ tonnes of CH₄, 1031.55 × 10⁴ tonnes of CO₂, 16,393.48 × 10⁴ tonnes of CO₂-eq) calculated by IPCC Tier 1 method, the carbon emissions calculated using our method based on in situ measurement were much lower than those of the IPCC method. This indicated that the carbon emissions of ONG systems in China were seriously overrated by the IPCC.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2016.09.051>.

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