Life Cycle Greenhouse Gas Emissions of Multi-pathways Natural Gas Vehicles in China Considering Methane Leakage

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Abstract

Natural gas has been promoted rapidly recent years to substitute traditional vehicle fuels. However, methane leakages in the natural gas supply chains make it difficult to ascertain whether it can reduce greenhouse gas emissions when used as a transport fuel. This paper characterizes the natural gas supply chains and their segments involved, estimates the venting and fugitive leakages from natural gas supply chains, decides the distribution among segments and further integrates it with life cycle analysis on natural gas fueled vehicles. Domestic natural gas supply chain turns out to be the dominant methane emitter, accounting for 67% of total methane leakages from natural gas supply chains. Transportation segments contribute 42%-86% of the total methane leakages in each supply chain, which is the greatest contribution among all the segments. Life cycle analysis on private passenger vehicles, transit buses and heavy-duty trucks show that compressed natural gas and liquefied natural gas bring approximately 11-17% and 9-15% greenhouse gas emission reduction compared to traditional fossil fuels, even considering methane leaks in the natural gas supply chains. Methane leakages from natural gas supply chains account for approximately 2% of the total life cycle greenhouse gas emissions of natural gas vehicles. The results ascertain the low-carbon attribute of natural gas, and greater efforts should be exerted to promote natural gas vehicles to help reduce greenhouse gas emissions from on-road transportation.

Keywords: natural gas supply chain; methane leakage; life cycle analysis on vehicles

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Abbreviations

CH_4	methane
CNG	compressed natural gas
CO_2	carbon dioxide
$CO_{2,e}$	carbon dioxide equivalent
cu.m.	cubic meters
GHG	greenhouse gas
GWP	global warming potential
LC	life cycle
LCA	life cycle analysis
LNG	liquefied natural gas
NG	natural gas
NGV	natural gas fueled vehicles
N_2O	nitrous oxide
PE	primary energies
PF	process fuels
PNG	pipelined natural gas
TLCAM	Tsinghua-LCA Model

Subscripts

i	natural gas supply chain
j	supply chain segment
k	facility used in natural gas supply chains
p_1	transmission pipelines in use in 2008
p_2	transmission pipelines in use in 2016
l	greenhouse gas type
r	fuel type
m	life cycle stages
n	process fuels

Variables

AL	average transmission distance
cap	annual transmission capacity of a pipeline
CC	carbon content
$ddist$	city natural gas distribution pipeline network length
$DFlow$	distribution flow
$dist$	annual transmission distance of a pipeline
EFF	fugitive emission factor of a specific facility of a year
EFV	venting emission factor of a specific facility of a year
EI	energy consumption in a specific life cycle analysis stage
EM	emission of a specific type of greenhouse gas
EMD	direct emission
$EMFF$	fugitive emission factor of a segment of a year based on flow
$EMFV$	venting emission factor of a segment of a year based on flow
EMU	upstream emission
F	flows of processing, distribution, storage, re-gasification and liquefaction segments
$Flow$	annual production flow
FOR	fuel oxidation rate
FR	fuel economy parameters
GWP	global warming potential value
$LCGE$	life cycle greenhouse gas emissions
$LEFD$	process fuel' direct emission factors
$LEFU$	process fuel' upstream emission factors
LR	leakage rate based on natural gas throughput
ML	methane leakages of different segments in natural gas supply chains
MLS	total methane leakage of a specific natural gas supply chain
NUM	quantity of a specific facility
PN	total primary NG consumption in life cycle analysis stages
SA	proportion that process fuels account for of the total energy consumption in a stage
TO	total natural gas throughput in China
η	processing efficiency

1. Introduction

Greenhouse gas (GHG) emissions have raised worldwide concern and China needs to control its carbon dioxide (CO_2) emission urgently [1]. Though decreased by 50 million tons to 9.1 billion tons between 2013 and 2016, CO_2 emission in China remains tremendous, accounting for 28% of total CO_2 emission in the world [2,3]. Transport sector gradually becomes a major contributor, accounting for 9.3% of total CO_2 emission in China [4], and a major consumer of petroleum resulting in significant and increasing dependence on energy import [5,6]. Natural gas (NG) is considered as a lower-carbon vehicle fuel and a potential substitute to gasoline and diesel [7]. Several relevant policies are promoted by the National Development and Reform Commission and several other government departments to encourage NG use in vehicles [8]. Therefore, NG consumption has enjoyed noticeable growth in recent years, increasing from 72 billion cubic meters (cu.m.) in 2008 to 208.7 billion cu.m. in 2016 [9,10]. NG import has increased rapidly these years, and in 2016, pipeline NG import from other countries was 38.61 cu.m., while liquefied natural gas (LNG) import was 26057.9 thousand tons. Pipeline NG was mainly imported from Turkmenistan, Uzbekistan, Myanmar and Kazakhstan. LNG was mainly imported from Australia, Qatar, Indonesia, Malaysia and Papua New Guinea [9,11]. Detailed percentages are shown in Fig. 1.

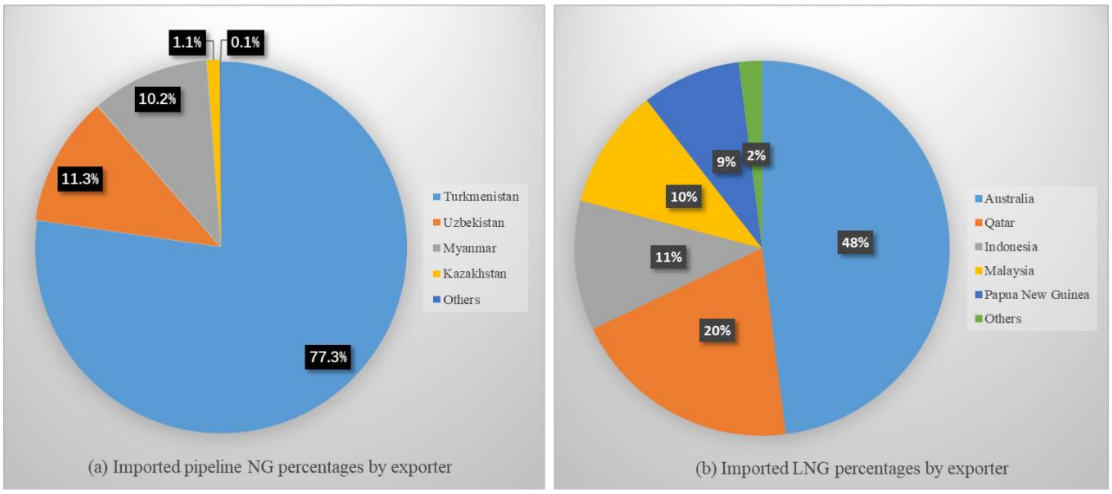

Fig.1. Imported pipeline NG and LNG percentages

Certain amounts of compressor stations, metering facilities and valves are required for a certain transport distance [12-14]. Several long-distance gas pipelines put into use these years in China have led to increase of facility quantities used in the transmission segment of the NG supply chains. Therefore, the gradually increasing pipeline transportation distances in China have led to higher methane leakage rates along the NG supply chains. Methane leakages have become a significant contributor to life cycle (LC) GHG emissions of NG used in vehicles [15-18]. The lower-carbon attribute of NG needs to be revisited if the methane leakage rate is too high as its GHG advantages over conventional fuels could diminish. Therefore, it is necessary to accurately estimate the GHG emissions from NG supply chains, especially those due to methane leakages, to compare the LC GHG emissions of NG use in vehicles with those of gasoline and diesel.

Several previous studies focused on the LC GHG emissions of NG fueled vehicles (NGV) [15, 19-23]. Ozbilen et al. [19] reviewed previous researches on NG heavy-duty vehicles and concluded that emission of NG-based tractors is 30% higher than conventional diesel vehicles. Tong et al. [15] compared the LC GHG emissions of NG pathways for medium and heavy-duty trucks. They found that compared to petroleum-based vehicles, LC emissions of compressed natural gas (CNG) and LNG vehicles increase by 0-3% and 2-13%, respectively. Delgado et al. [20] used data on energy efficiency and energy consumption in previous studies and conducted life cycle analysis (LCA) on NGVs. Their results indicate that 28% less CO_2 emission from NGVs is achieved compared to diesel fueled vehicles. Arteconi et al. [21] adopted LCA to compare diesel and LNG in vehicles in Europe, and they found a 14% GHG emission reduction with LNG use. Huo et al. [22] estimated the LC GHG emissions of electric vehicles and CNG vehicles at a provincial level and the results showed noticeable variation among provinces. Ou et al. [23] estimated LC energy use and GHG emissions of different NG-based vehicles taking carbon capture and storage technology into account. They found that CNG and LNG can help reduce LC GHG emissions by 10% compared to gasoline.

Several studies focused on methane leakages from NG supply chains [24-28]. P. Balcombe et al. [24] analyzed the methane and GHG emissions of NG supply chains following a log-log-logistic distribution with mean emission turning out to be 0.8-2.2% of the total methane production. McKain et al. [25] estimated average emission rate of each segment in the NG supply chains in Boston and the results indicate that methane emission from NG delivery and end use is 18.5 g per square meter of urban area per year. Allen et al. [26] reported statistics about methane emissions from 150 NG production sites and recorded emissions from different processes. Itaru Tamura et al.

[27] calculated the emissions from LNG use, taking several supply chain stages into account. Littlefield et al. [28] adopted ground-based field measurements and concluded that during the NG extraction and delivery process the emission rate is 1.7%.

However, the aforementioned studies fail to provide sufficient China specific information about methane leakages from diverse NG supply chains in China and LC GHG emissions of NG-fueled vehicles in China, which are necessary to conclude whether LC GHG emissions of NG pathways in China are lower than gasoline and diesel when methane leakages from NG supply chains are properly considered. In particular, the following three key aspects are lacking: 1) an accurate characterization of different NG supply chains and the segments involved in each supply chain in China; 2) an estimate of both current fugitive and venting leakages during the supply and delivery process of NG; and 3) methane leakage rate based on NG throughput by segment for each NG supply chain in China and its integration into vehicle LCA.

Therefore, this study aims to accomplish the following three important tasks: 1) to define different potential leakage stages of NG supply chains; 2) to quantify venting and fugitive leakages in the NG supply chains and define the emission distribution of certain proportions of the NG supply chain; and 3) to conduct a comprehensive analysis on LC emissions of NGVs to determine whether NG is indeed a lower-carbon vehicle fuel.

The main novelty of this study includes: 1) the adoption of a bottom-up method to quantify methane leakages of NG supply chains by segment in China, which can also be used for other regions or countries if data are available; and 2) the integration of NG throughput-based methane leakage rates into vehicle LCA to evaluate the emission performance of NG-based fuels in China.

This paper is structured as follows: **Section 2** introduces NG segment definition and methodology adopted for methane leakage quantification; **Section 3** presents the data and assumptions used; **Section 4** illustrates the major results of this study in comparison with several other relevant studies; and finally **Section 5** draws conclusions and policy implications. Methodology for vehicle LCA is shown in **Appendix A**.

2. Methodology

2.1 Research Boundary

This study adopts the Tsinghua-LCA Model (TLCAM) to fulfil the LC GHG emission analysis for various types of vehicles and vehicle-fuel pathways in China. The platform includes several main stages: feedstock extraction and processing, feedstock transportation, fuel production, fuel transportation and fuel use in vehicles [29,30]. This study mainly focuses on the fuel cycle, while the vehicle cycle including vehicle manufacturing and recycling processes is not considered in this research. TLCAM covers three major GHGs: CO_2, Nitrous Oxide (N_2O) and methane (CH_4). The research boundary for methane emission estimation is further extended to include methane leakages from NG supply chains in this platform. Fugitive and venting methane leakages during the production, processing, transportation, distribution, storage, re-gasification and liquefaction segments of NG supply chains are taken into account using localized data. The methane leakage rates estimated based on the total NG throughput are integrated into the corresponding LCA stages. Detailed research boundary is shown in Fig. 2.

Several studies categorize vehicles by tonnages. However, data about vehicle fuel economy in China are not specific enough, and average fuel economy for standard vehicle type is adopted in this study. Vehicle types covered in this study include private passenger vehicles, transit buses and heavy-duty trucks, shown in Table 1 referred from the Ministry of Public Security of China and literature reviews [31-33]. LC GHG emissions of each type of NGVs are compared with their corresponding diesel and gasoline vehicles.

The functional units for energy consumption and GHG emissions adopted in this study are MJ per kilometer (MJ/km) and g CO_2-equivalent per kilometer (g $CO_{2,e}$/km), respectively, based on the travelling distance of the vehicle. Both direct GHG emissions and indirect GHG emissions including the emissions resulted from power used in compressor stations and gas production are involved in the TLCAM. Detailed calculation principles for LCA on vehicles are shown in Appendix A. Energy consumption from fuel stations is non-negligible [34,35], and energy consumption and GHG emissions from compressing and liquefaction processes in the fuel station are considered in the fuel production segments.

Table 1. Vehicle characteristics in this study

Vehicle type	Tonnage (tons)	Vehicle characteristics
Private passenger vehicles	1.1~1.4	The vehicle is shorter than 6 meters long and carries less than 9 passengers
Transit buses	12.5~14.5	The vehicle is beyond 6 meters long and carries more than 20 passengers
Heavy-duty trucks	20~25	The vehicle is beyond 6 meters long

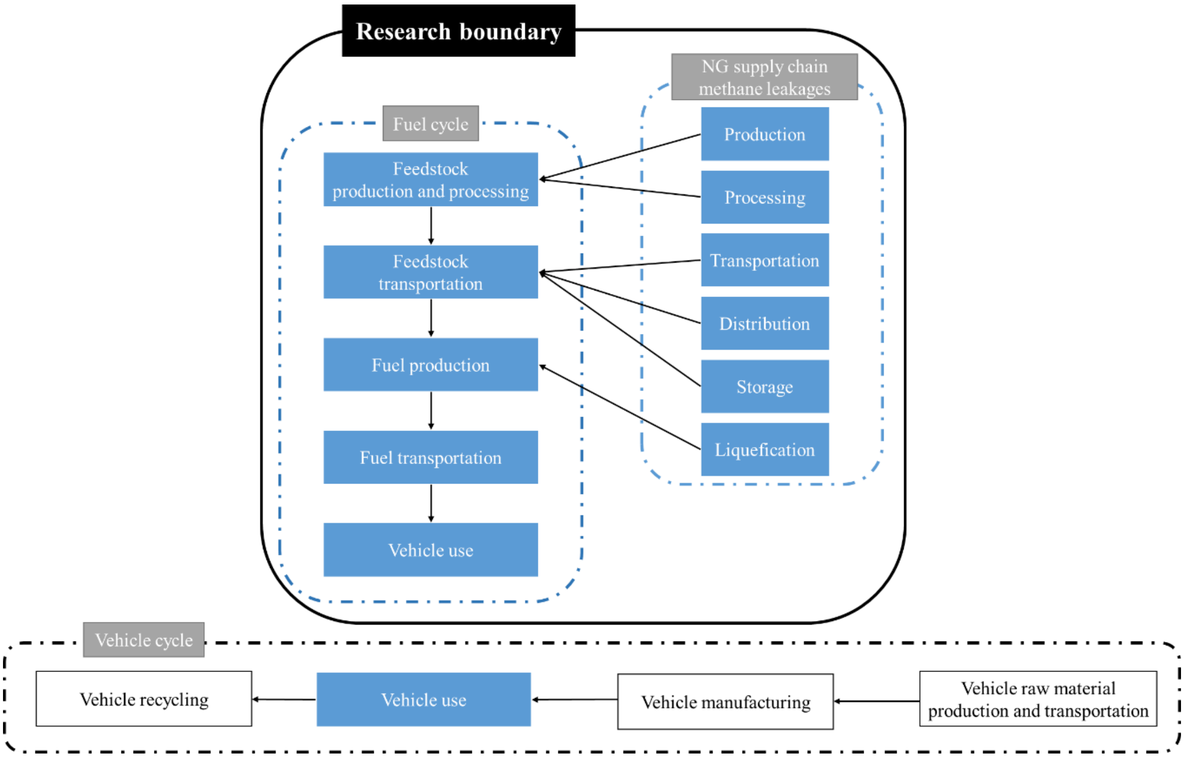

Fig.2. Research boundary of this study

2.2 Methane Leakages from NG Supply Chains

This study characterizes various segments involved in the NG supply chains and defines the contribution of each segment to the total methane leakages from NG supply chains through a bottom-up method. The leakage rate by segment based on total NG throughput is obtained.

2.2.1 NG Supply Chain and Segment Definition

The research boundary of this study includes the following four NG supply chains: domestic NG, domestic LNG, LNG import and pipelined natural gas (PNG) import. Seven segments are defined in these four supply chains. Table 2 shows the segments involved in each of supply chain. Transportation segments denote long-distance transport while distribution segments mainly represent urban NG pipeline network. Detailed framework can be seen in Fig. 3.

Table 2. Segments involved in the four supply chains

Segments	Domestic NG	Domestic LNG	Import LNG	Import PNG
Production	✓	✓	×	×
Processing	✓	✓	×	×
Transportation	✓	✓	✓	✓
Distribution	✓	✓	✓	✓
Storage	✓	×	×	×
Regasification	×	×	✓	×
Liquefaction	×	✓	×	×

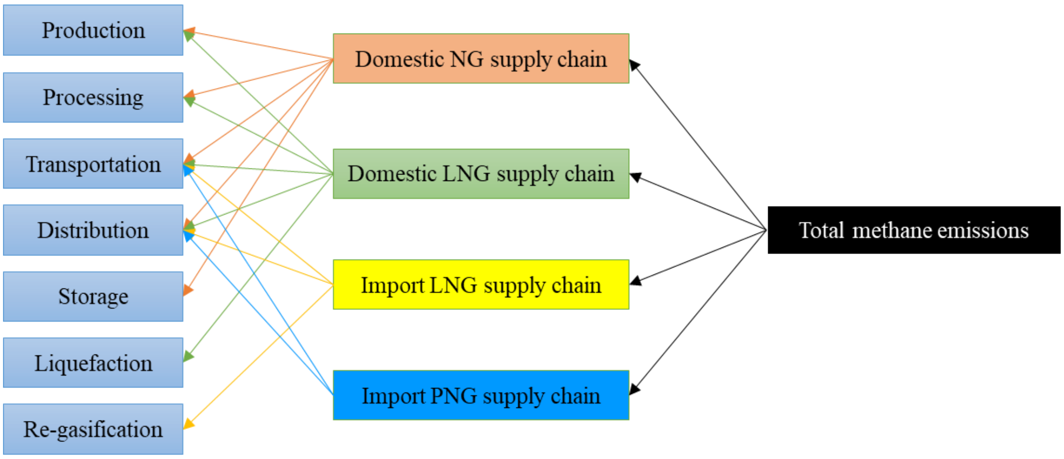

Fig.3. NG supply chain characterization

2.2.2 Methane Leakages from NG Supply Chains

For each supply chain, methane leakages are calculated by summing up methane leakages of different segments involved in that supply chain, as Eq. (1) shows.

$$MLS_i = \sum_j ML_{i,j} \tag{1}$$

Where subscript *i* denotes the NG supply chains, subscript *j* denotes the segments in the supply chains, *MLS* denotes the total methane leakage of a certain supply chain, and *ML* denotes methane leakages from different segments.

For the production and transportation segments of each supply chain *i*, we adopt Tier3 raised by IPCC Guideline 2006 [36], as Eq. (2) shows.

$$ML_{i,j} = \sum_k \left[NUM_{i,j,k} \times (EFV_{i,j,k} + EFF_{i,j,k}) \right] \tag{2}$$

Where *k* denotes facilities used in this segment, *ML* denotes methane leakages, *NUM* means the quantity of a specific facility, *EFV* means the venting emission factor of a specific facility for a year, and *EFF* means the fugitive emission factor of a specific facility for a year.

We assume that the quantities of facilities in the production segments are related to the production flows. Therefore, based on the data we obtained, the activity level of production segment is scaled up based on the volume of NG production in 2008 and 2016 and the number of diverse facilities employed in the production segments in 2008, as shown by Eq. (3), the availability and feasibility of which are verified through expert consultation.

$$NUM_{i,j,k} = NUM_{i,j,k,2008} \times \frac{Flow_{i,2016}}{Flow_{i,2008}} \tag{3}$$

Where $NUM_{i,j,k,2008}$ denotes the number of facilities in 2008 from the data we obtained, $Flow_{i,2016}$ and $Flow_{i,2008}$ are the volumes of production segments in 2016 and 2008, respectively.

Quantities of facilities in the transportation segments are not only relevant to the transportation distances of major NG transmission pipelines but also their corresponding annual transmission capacities. Therefore, as for the transportation segments of NG supply chains, activity levels are scaled up based on the turnover of 2008 and 2016 and the number of diverse facilities employed in the transportation segments in 2008. The turnovers of transportation segments are calculated by summing up the product of transmission distance and capacity of the main long-distance NG transmission pipelines, since these main pipelines account for almost all long-distance NG transmission in China [11,14]. The feasibility and reliability of this method are verified through expert consultation. Detailed calculation principle is shown in Eq. (4).

$$NUM_{i,j,k} = NUM_{i,j,k,2008} \times \frac{\sum_{p_2} cap_{p_2} \times dist_{p_2}}{\sum_{p_1} cap_{p_1} \times dist_{p_1}} \tag{4}$$

Where subscript p_1 and p_2 represents various NG transmission pipelines in 2008 and

2016 respectively, *cap* denotes the annual transmission capacity of a specific pipeline and *dist* denotes its corresponding transmission distance, $NUM_{i,j,k,2008}$ denotes the number of facilities in 2008 from the data we obtained.

For the processing, distribution, regasification and liquefaction segments, we adopt Tier2 raised by IPCC Guideline 2006 [36]. As for the storage segment, Tier1 is employed. Calculation principles are shown in Eq. (5).

$$ML_{i,j} = F_{i,j} \times (EMFV_{i,j} + EMFF_{i,j}) \tag{5}$$

Where subscript j denotes different segments, F means the flow of the segment, *EMFV* means the venting emission factor of the segment for a year based on the flow, *EMFF* means the fugitive emission factor of the segment for a year based on the flow.

The flows of the processing segments in 2016 are derived from the processing efficiency and the flow of production segment, as Eq. (6) shows.

$$F_{i,j} = Flow_{i,2016} \times \eta \tag{6}$$

Where η means the processing efficiency in 2016.

The flows of the distribution segments are scaled up based on the urban NG distribution pipeline network distance, as Eq. (7) shows.

$$F_{i,j} = DFlow_{i,2008} \times \frac{ddist_{2016}}{ddist_{2008}} \tag{7}$$

Where $DFlow_{i,2008}$ represents the distribution flow in 2008, $ddist_{2016}$ and $ddist_{2008}$ denotes the total urban NG distribution pipeline length in 2016 and 2008, respectively.

2.2.3 Leakage Rate by Segment Based on NG Throughput

The leakage rate of each segment based on total throughput is calculated by Eq. (8), which will be integrated into LCA of NG-based vehicles.

$$LR = \frac{ML}{TO} \tag{8}$$

Where *LR* is the leakage rate of each segment in the NG supply chain (%), *TO* means the total NG throughput in China.

Methane leakage rate per unit NG produced per unit distance transmitted for the transportation segment is calculated through Eq. (9).

$$LR = \frac{ML}{TO \times AL} \tag{9}$$

Where *AL* is the average NG transmission distance in 2016.

3. Data and Key Assumptions

Several key sets of data are required to obtain the final results based on the methodology mentioned above: 1) activity levels of different segments in the NG supply chains; 2) methane leakage factors of different segments in the NG supply chains; 3) fuel economy for different types of vehicles; 4) primary energy intensity of the fuel cycle; and 5) GHG emission factors of the fuel cycle.

3.1 NG Supply Chain Activity Level

We obtain the flows of diverse segments from China Energy Statistical Yearbook 2017, China National Petroleum Corporation Yearbook 2017, China Petrochemical

Corporation Yearbook, China Statistical Yearbook and a scientific report [9,14,37-40], as Table 3 shows. For the processing segment, the flow is obtained based on the processing efficiency in the scientific report produced by Tsinghua University [14] and the production flow in 2016 [9]. The transmission pipeline distance of distribution network is derived from [11]. For the storage segment, we only take flows of China National Petroleum Corporation and China Petrochemical Corporation [37,39] into account, as flows of other corporations are negligible. For the re-gasification segment, we assume that all of the domestic LNG is consumed in the liquid form and re-gasification is only required for part of the imported LNG. This means the re-gasification flow is obtained through the total LNG import minus the imported LNG used directly in the liquid form. The quantity of LNG used directly is derived from [40]. The processing efficiency is derived from [14] and set to be 95.9% in this study. The activity flows in 2016 are shown in Table 3.

The quantities of facilities in the production segment in 2016 are scaled up based on the flow of NG in 2008 and 2016 and the quantities of diverse facilities in 2008 [9,14], as Table 4 shows. The activity levels of transportation segment are scaled up based on the summation of the product of pipeline length and flow in 2008 and 2016 and the quantities of facilities in 2008 [11,14,38], as shown in Table 5. Detailed facility numbers are shown in Table 6. Detailed activity levels of different segments of NG supply chains in 2008 are shown in Appendix B.

Table 3. Flows of the production, processing, distribution, storage, regasification

and liquefaction segments in 2016 (Source: [9,14,37-40])

Segments	Unit	Domestic NG	Domestic LNG	Import LNG	Import PNG
Production	billion cu.m	126.5	10.4		
Processing	billion cu.m	121.4	9.9		
Distribution	billion cu.m	22.8	1.7	6.5	6.6
Storage	billion cu.m	6.4			
Re-gasification	thousand tons			20827.9	
Liquefaction	thousand tons		7065.5		

Note. Processing flow is obtained based on the production flow [9] and processing efficiency derived from [14].

Table 4. Quantity of facilities in the production segment in 2016 (Unit: set)

Facility category	Domestic NG	Domestic LNG
Wellhead assembly	11806	967
Low-pressure and heating NG gathering system	765	63
Dehydration NG gathering system	95	8
Metering/ gas distribution system	5296	434
NG storage station	346	28

Note. Scaled up based on the flow of 2008 and 2016 and the quantities of facilities in the production segment obtained from the scientific report in 2008 [14]; facility quantities and flows in 2008 are shown in Appendix B; Flows in 2016 are derived from [9]

Table 5. Long-distance pipeline put into use in 2008 and 2016

Year	Pipeline	Distance (km)	Annual transmission capacity (billion cu.m)
2016	Shaanxi-Beijing Gas Pipeline	1256	3.3
	Shaanxi-Beijing Gas Pipeline Second Line	932	12
	Shaanxi-Beijing Gas Pipeline Third Line	1000	15
	West-east Gas Pipeline	4000	12
	West-east Gas Pipeline Second Line	9000	30
	West-east Gas Pipeline Third Line	7050	30
	Sichuan-east Gas Pipeline	1702	12
2008	Shaanxi-Beijing Gas Pipeline	1256	3.3
	Shaanxi-Beijing Gas Pipeline Second Line	932	12
	West-east Gas Pipeline	4000	12

Note. Data is derived from [11]

Table 6. Quantity of facilities in transportation segment in 2016

Facility category	Domestic NG	Domestic LNG	Import LNG	Import PNG
Compressor/ booster station	1240	96	352	378
Metering device	3586	276	1019	1095
Pipeline	2486	192	707	759
Pigging station	42187	3252	11992	12876

Note. The activity levels are scaled up based on the specific capacity and transportation distance of each pipeline in 2008 and 2016 respectively and the facility quantities in the transportation segment obtained from the scientific report in 2008 [11,14,38].

3.2 Methane Emission Factor of Different Segments in the NG Supply Chains

We obtain the methane emission factors from the Tsinghua scientific report and literature reviews [14,41,42]. Table 7 shows the fugitive and venting methane emission factors of different facilities in the production and transportation segments. Flow-based fugitive and venting methane emission factors of other segments are listed in Table 8.

Table 7. Methane emission factors of facilities in production and transportation segments (Unit: ton per set of facility per year; source: [14])

Facility category	Fugitive emission factor	Venting emission factor
	EFF	***EFV***
Production segment		
Wellhead assembly	2.495	0.000
Low-pressure and heating NG gathering system	27.900	23.599
Dehydration NG gathering system	1.240	3.248
Metering/ gas distribution system	8.473	0.000
NG storage station	58.373	10.036
Transportation segment		
Compressor/ booster station	85.047	10.055
Metering device	31.496	13.519
Pipeline	0.852	5.488
Pigging station	0.000	0.001

Table 8. Methane emission factors of the processing, distribution, storage, regasification and liquefaction segments

Segments	Unit	***EMFF***	***EMFV***	Data Source
Processing	ton per billion cu.m per year	403.41	138.33	[14]
Distribution	ton per billion cu.m per year	1330.00	--	[14]
Storage	ton per billion cu.m per year	41.50	0.00	[41]
Regasification	ton per thousand tons per year	0.1356	0.00	[42]
Liquefaction	ton per thousand tons per year	1.47	0.00	[42]

3.3 Parameters Related to Vehicle LCA

Parameters relevant to LC GHG emission estimation of vehicles include the primary energy intensities, carbon content, fuel oxidation rate and their corresponding GHG emission factors involving the upstream and direct emission factor as shown in Tables 9 and 10. Three primary energies (PE) – coal, NG and oil – and four process fuels (PF) – diesel, gasoline, residue oils and electricity – are taken into account [29,30]. Data in Table 9 indicates the primary energy consumption because of 1 MJ of each type of process fuel utilized in the LC process. Table 10 indicates the corresponding carbon content, fuel oxidation rate and emission factors. The emission factors reflect the GHG emission when 1 MJ of each type of process fuel is used. We suppose that CNG is only used around regions with rich NG resources, particularly Sichuan and Xinjiang Provinces. The transmission distance for CNG production is derived from expert consultation and literature reviews [43-45]. For the CNG pathway, NG is assumed to be transmitted over 300 km, compressed locally and then put into use in vehicles. For the LNG pathway, NG is assumed to be liquefied locally and then transported by road to the destination for vehicle use. CO_2-equivalent GHG emissions of nitrous oxide and methane are calculated based on their corresponding 100-year Global Warming Potential (GWP) values, derived from literature reviews [46, 47]. Global Warming Potential values for methane and nitrous oxide in this study are 25 and 298, respectively.

Table 9. Primary energy intensities for process fuels in China (Unit: MJ/MJ, Source: [23,29,30,43])

PF	Raw coal	Raw NG	Raw Oil
Coal	1.07	0.00	0.02
NG	0.04	1.06	0.05
Diesel	0.07	0.06	1.14

Gasoline	0.08	0.03	1.15
Residue oil	0.06	0.06	1.11
Electricity	2.3	0.18	0.07

Table 10. Parameters relevant to direct and indirect GHG emissions from various types of process fuels (Source: [23,29,30,43,48])

Items	Variables	Unit	Coal	NG	Diesel	Gasoline	Residue oil	Electricity
Carbon content	*CC*	g/MJ	24.080	15.300	20.200	18.900	21.100	--
Fuel oxidation rate	*FOR*	g/MJ	0.900	0.990	0.980	0.980	0.980	--
Direct CO_2 emission factor	*LEFD*	g/MJ	79.460	55.540	72.590	67.910	75.820	--
Direct CH_4 emission factor	*LEFD*	g/MJ	0.001	0.001	0.004	0.080	0.002	--
Direct N_2O emission factor	*LEFD*	mg/MJ	0.001	0.001	0.002	0.002	0.000	--
Upstream CO_2 emission factor	*LEFU*	g/MJ	5.776	9.660	18.575	19.216	14.022	181.507
Upstream CH_4 emission factor	*LEFU*	g/MJ	0.434	0.093	0.041	0.042	0.034	0.877
Upstream N_2O emission factor	*LEFU*	mg/MJ	0.127	0.403	0.406	0.411	0.360	2.848

NG processing efficiencies for CNG and LNG are shown in Table 11. LNG pathway considered in the LC GHG emission analysis is based on domestically produced LNG.

Table 11. Processing energy efficiencies for different NG-based fuel pathways (Source: [43])

NG-based fuels	NG plant energy efficiency	PF consumption composition
CNG	96.9%	NG (97%) and electricity (3%)
LNG	91.0%	NG (98%) and electricity (2%)

3.4 Vehicle Fuel Economy

Average fuel economy of three types of vehicles running on different types of fuels are derived from literature reviews [48-51] and shown in Table 12. The energy efficiencies of diesel, gasoline, CNG and LNG fuels for the same type of vehicle are assumed to be the same.

Table 12. Fuel consumption rate of different vehicles in China (Source: [48-51])

Fuel type	Unit	PPV	TB	HDV
Diesel	L/100 km	--	28.0	33.0
Gasoline	L/100 km	8.5	--	--
LNG	L/100 km	13.8	57.4	67.6
CNG	m^3/100 km	8.3	34.5	40.7

4. Results and Discussions

4.1 NG Supply Chain Methane Leakages

4.1.1 Methane Leakages from different NG Supply Chains in China

Table 13 presents the results for total methane leakages from the NG supply chains in China. According to our estimation, total leakage amounts to 787.82 thousand tons in 2016 (see Table 13). Share in final throughput in Table 13 indicates the leakages from each segment as volumetric percentages of the final NG throughput, i.e., overall NG output from all supply chains in the NG industry (0.14 billion tons in 2016). Leakage during long-distance transportation is the most significant contributor to total leakage. The overall leakage rate per final throughput increased from 0.39% in 2008 to 0.57% in 2016, mainly because of a significant increase in the transportation segment even with decreases in the production and processing segments.

Table 13. Total methane leakages from NG supply chains in China in 2016

Segments	Leakage (Unit: 10^3 tons)	Volumetric share in final throughput (Unit: %)
Production	131.01	0.09
Processing	71.12	0.05

Re-gasification	2.82	0.00
Transportation	491.91	0.36
Storage	0.27	0.00
Liquefaction	10.39	0.01
Distribution	80.3	0.06
Total	787.82	0.57

Note. The denominator of “volumetric share in final throughput” is the total throughput of NG industry available for consumption.

Table 14 shows methane leakages from different segments in each NG supply chain in 2016. Transportation segment is the major contributor to leakages, accounting for 42%-86% of the total for the four supply chains considered. Production segment leakages are significant for the domestic NG and domestic LNG supply chains, accounting for 22% and 21% of the total leakages from the two chains, respectively. Distribution leakages are non-negligible for the import LNG and import PNG supply chains, accounting for approximately 7% and 14% of the total leakages from the two chains, respectively.

Methane leakage from the domestic NG supply chain, approximately 529.08 thousand tons, is the greatest among the four chains. Methane leakages from the production, processing, transportation, storage and distribution segments in this supply chain are 119.73, 65.74, 295.16, 0.27 and 48.18 thousand tons, respectively. Overall volumetric leakage rate per unit NG produced is 0.64% and transportation and production segments together contribute to 78% of the total leakage from this chain.

For the LNG import supply chain, methane leakage during transportation is the dominant segment with approximately 83.91 thousand tons. Leakages during re-gasification and distribution are 2.82 and 13.70 thousand tons, respectively. Overall volumetric leakage rate of this supply chain is 0.39%.

Although the domestic LNG supply chain has the lowest total methane leakage (100.43 thousand tons) among the four chains, its overall leakage rate is the highest (0.76%). This is mainly because noticeable methane leakages from the liquefaction segment in this supply chain. Methane leakages in the production, processing, transportation, liquefaction and distribution segments are 11.28, 5.38, 22.75, 10.39 and 3.71 thousand tons, respectively.

For the PNG import supply chain, methane leakages during transportation and distribution are approximately 90.09 and 14.71 thousand tons, respectively. The overall leakage rate of this supply chain is 0.42%.

Table 14. Methane leakages from different segments in each NG supply chain in 2016 in China

Domestic NG supply chains			**LNG import supply chains**		
Segments	Leakages Unit: 10^3 tons	Percent Unit: %	Segments	Leakages Unit: 10^3 tons	Percent Unit: %
Production	119.73	0.14	Re-gasification	2.82	0.01
Processing	65.74	0.08	Transportation	83.91	0.33
Transportation	295.16	0.36	Distribution	13.70	0.05
Storage	0.27	0.00			
Distribution	48.18	0.06			

Total	529.08	0.64	Total	100.43	0.39

Domestic LNG supply chains			**PNG import supply chain**		
Segments	Leakages Unit: 10^3 tons	percent Unit: %	Segments	leakages Unit: 10^3 tons	percent Unit: %
Production	11.28	0.16	Transportation	90.09	0.36
Processing	5.38	0.08	Distribution	14.71	0.06
Transportation	22.75	0.32			
Liquefaction	10.39	0.15			
Distribution	3.71	0.05			
Total	53.51	0.76	Total	104.80	0.42

Note. "Percent" denotes the "volumetric percentage of final throughput", and the denominator is the total throughput of each NG supply chain available for consumption.

4.1.2 Methane Leakage Rate of NG Supply Chains in China

Based on the above estimation results on the methane leakages from different segments in specific NG supply chains, several key leakage parameters can be obtained (see Table 15). Methane leakage rate during production and processing is 0.22% of total NG produced. Leakage rate during long-distance NG transportation will be 0.13% of total NG transmitted for every 1000 km. The methane loss rate of liquefaction process is 0.15%.

Table 15. Key methane leakage parameters

Emission rates from diverse segments	Unit	Value
Production and processing for domestic NG supply	% per NG produced	0.22%
Long-distance NG transportation	% per 1000 km	0.13%
Liquefaction	% per LNG produced	0.15%

4.2 LC GHG Emissions of Different Types of NGVs

The methane leakages from production and processing segments, transportation segments and liquefaction segments are obtained from the product of the LC NG consumption and methane leakage rates of different segments, which are shown in Table 15. LC GHG emissions of NG-based private passenger vehicles are shown in Fig 4. For the CNG pathway, methane leakages from the NG production and processing and NG transportation segments are 3.21 and 0.57 g CO_2-equivalent ($CO_{2,e}$) per vehicle km travelled, respectively. For the LNG pathway, methane leakages from NG production and processing and liquefaction segments are 3.07 and 1.00 g $CO_{2,e}$ per vehicle km travelled, respectively. Overall LC GHG emissions are 242.30, 200.43 and 204.96 g $CO_{2,e}$ per vehicle km travelled for gasoline, CNG and LNG vehicles, respectively. LC GHG emissions of CNG and LNG vehicles are about 17% and 15% less than that of traditional gasoline vehicles, respectively.

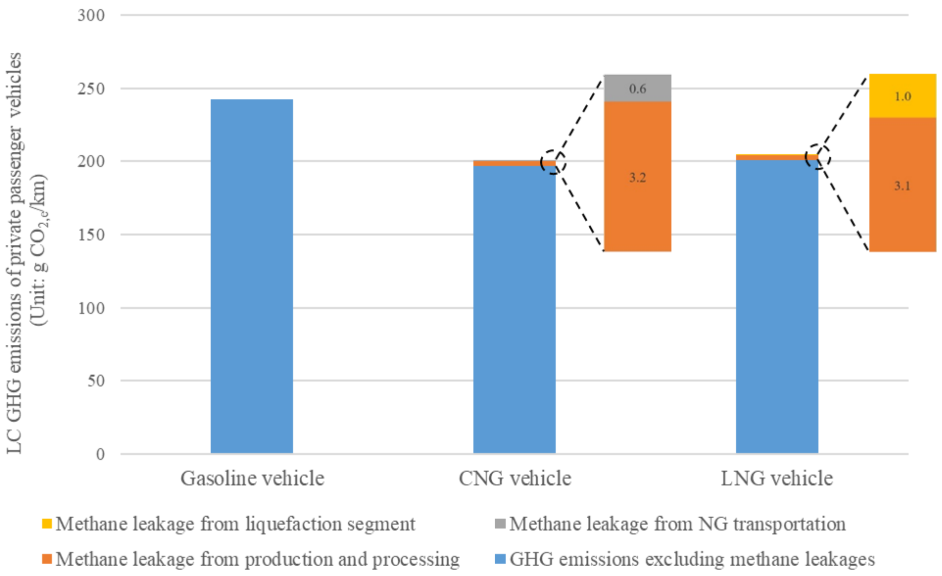

Fig.4. LC GHG emissions of private passenger vehicles with methane leakages taken into consideration. Note: Specific LC methane leakages of CNG and LNG vehicles are shown in column beside the column representing the total LC GHG emissions

LC GHG emissions for diesel, CNG and LNG transit buses are shown in Fig 5. For the CNG pathway, methane leakages from the NG production and processing and NG transportation segments are 13.36 and 2.37 g $CO_{2,e}$ per vehicle km travelled, respectively. For the LNG pathway, methane leakages from NG production and processing and liquefaction segments are 12.76 and 4.17 g $CO_{2,e}$ per vehicle km travelled, respectively. Overall LC GHG emissions of the CNG and LNG pathways are 833 and 852 g $CO_{2,e}$ per vehicle km travelled, respectively, both lower than that of the diesel pathway (937 g $CO_{2,e}$ per vehicle km travelled). The reduction rates turn out to be about 11% and 9% for CNG and LNG, respectively.

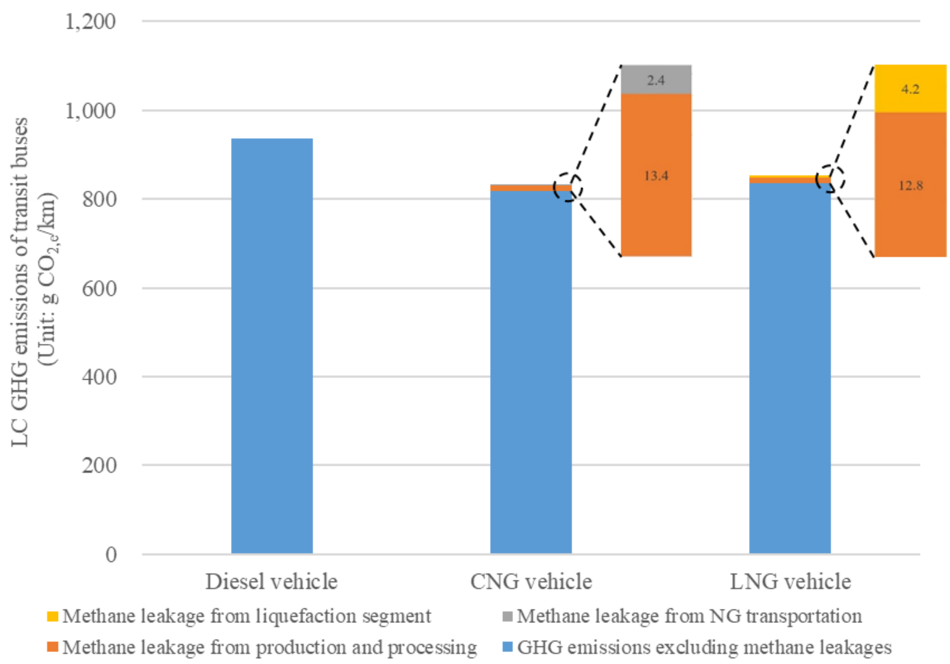

Fig.5. LC GHG emissions of transit buses with methane leakages taken into consideration. Note: Specific LC methane leakages of CNG and LNG vehicles are shown in column beside the column representing the total LC GHG emissions

Fig. 6. presents the results for heavy-duty trucks. Methane leakages from the NG production and processing and NG transportation segments are 15.74 and 2.79 g $CO_{2,e}$ per vehicle km travelled for the CNG pathway, respectively. For the LNG pathway, methane leakages from NG production and processing and liquefaction segments are 15.04 and 4.91 g $CO_{2,e}$ per vehicle km travelled, respectively. Although methane leakages are taken into consideration, overall LC GHG emissions of CNG and LNG fueled heavy-duty trucks are about 11% and 9% less than that of diesel vehicles, respectively.

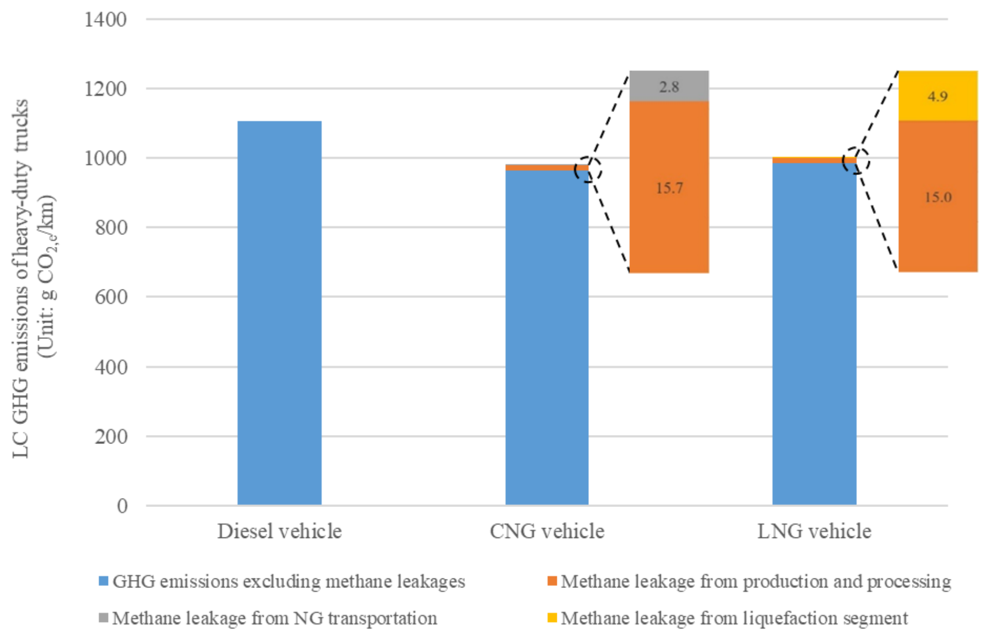

Fig.6. LC GHG emissions of heavy-duty trucks with methane leakages taken into consideration. Note: Specific LC methane leakages of CNG and LNG vehicles are shown in column beside the column representing the total LC GHG emissions

The results above indicate that methane leakages account for approximately 1.9% and 2.0% of the total LC GHG emissions for CNG and LNG used in NGVs, respectively. The overall LC GHG emission performance of NG-based fuels in China is better than traditional fossil fuels even when the venting and fugitive leakages from NG supply chains are taken into account.

4.3 Comparative Analysis with Other Studies

4.3.1 Comparative Analysis on NG Supply Chain Leakages

Several other studies conducted analysis on NG supply chain methane leakage rate in China and the U.S. (see Table 16). The overall supply chain leakage rate estimated in this study is lower than those in the U.S. studies and higher than other studies on NG supply chains in China. Leakage rates of the production, processing and distribution segments in U.S. NG supply chains derived from direct site measurement are 0.42%, 0.47% and 0.10-0.22%, respectively. The methane leakage rates in China are lower mainly because most of the facilities in China are newly installed. The results from this study are higher than previous studies focusing on China mainly because this study offers a more comprehensive and detailed analysis on the NG supply chains in China and employs more up-to-date data.

Table 16. Comparison of methane leakage estimates in different studies

Relevant studies	Location	Method	Detailed segment	Leakage amount (tons)	Leakage rate (%)
This study	China	Bottom-up accounting	Total NG supply chains	7.9×10^5	0.57
Littlefield et al.[28]	U.S.	Bottom-up accounting	Total NG supply chains	--	1.70
Cai et al.[34]	U.S.	Literature review and site measurement	Total NG supply chains	--	1.34
Allen et al. [26]	U.S.	Sites measurement	NG Production	2.3×10^6	0.42
Marchese et al.[52]	U.S.	Sites measurement	Gathering and processing	2.4×10^6	0.47
Lamb et al. [53]	U.S.	Direct measurement	Distribution	3.9×10^5	0.10-0.22
Balcombe et al.[24]	Worldwide	High-resolution emission measurement	Total NG supply chain	--	0.90
Zhang et al. [54]	China	Bottom-up accounting	Total NG supply chain	4.0×10^5	0.41
Zhang et al. [55]	China	Bottom-up accounting	Total NG supply chain	3.9×10^5	--

Note: the leakage rate is the methane leakage from NG supply chains per unit NG produced.

Overall methane leakage rate per final NG output in China increased from 0.39% in 2008 [14] to 0.57% in 2016, mainly resulted from increase in the transportation segment. This is mainly because the transmission distance has increased as several new pipelines were put into use recently, which is mentioned in the previous section. Leakages from the production and processing segments decreased as the NG import has increased rapidly. Detailed leakage rates in 2008 are shown in Table 17.

Table 17. Methane leakages in China in 2008

	Total methane leakages	2008 Percent of Final Output (%)
Unit	thousand tons	%
Production	82.88	0.17
Processing	39.55	0.07
Transportation	50.94	0.10
Distribution	22.62	0.05
Total	195.99	0.39

It should be noted that the estimations in this paper are relatively conservative because of conservative emission factors adopted in this study. The emission factors could have been improved since 2008 and as a result actual current methane leakages from NG supply chains and the LC GHG emissions of NG-based fuels could be lower than those estimated in this study.

4.3.2 Comparative Analysis on LC GHG Emissions of NGVs

Relevant studies on LC GHG emissions from light-duty vehicles, transit buses and heavy-duty trucks are shown in Figs 7, 8 and 9. The emissions from gasoline, CNG and

LNG private passenger vehicles are found to be higher in this study than a previous study adopting TLCAM [23] as methane leakages from NG supply chains are taken into consideration and energy-related parameters are updated. However, the emission results in this study are lower than results in several other studies because of the differences in fuel economy and processing efficiencies used and higher methane emission rates used in other studies. LC GHG emission rates of a transit bus and a heavy-duty truck in this study are generally lower than other studies (see Figs 8 and 9) mainly because of the higher energy efficiencies used in this study. All studies found that NGVs have lower LC GHG emissions than conventional fuel vehicles except one study on diesel and CNG heavy trucks.

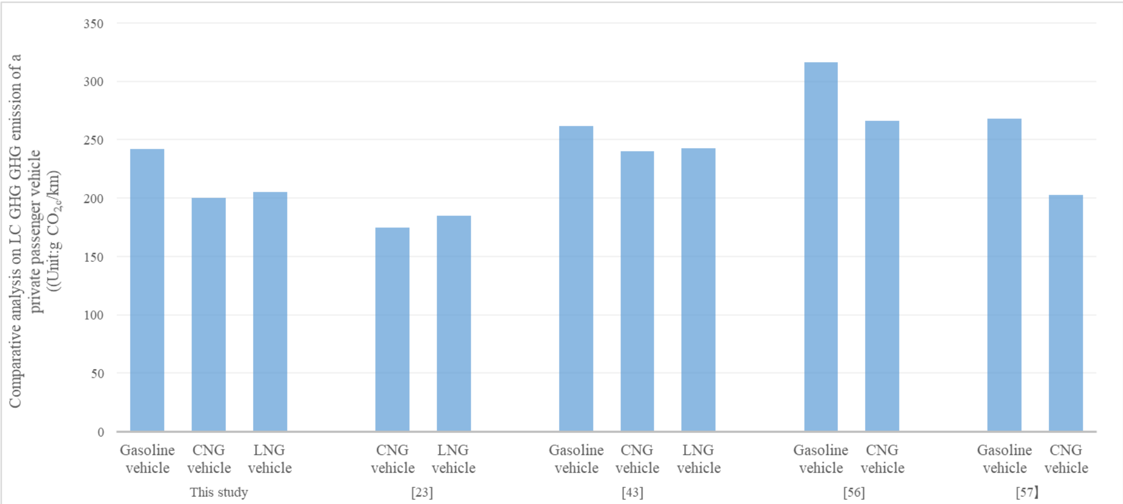

Fig.7. LC GHG emissions of gasoline, CNG and LNG private passenger vehicles in different studies

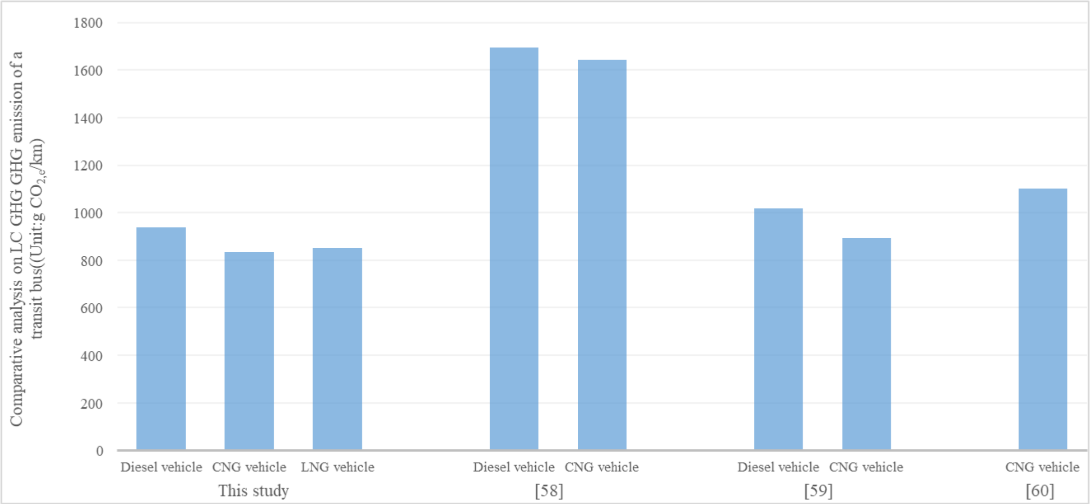

Fig.8. LC GHG emissions of diesel, CNG and LNG transit buses in different studies

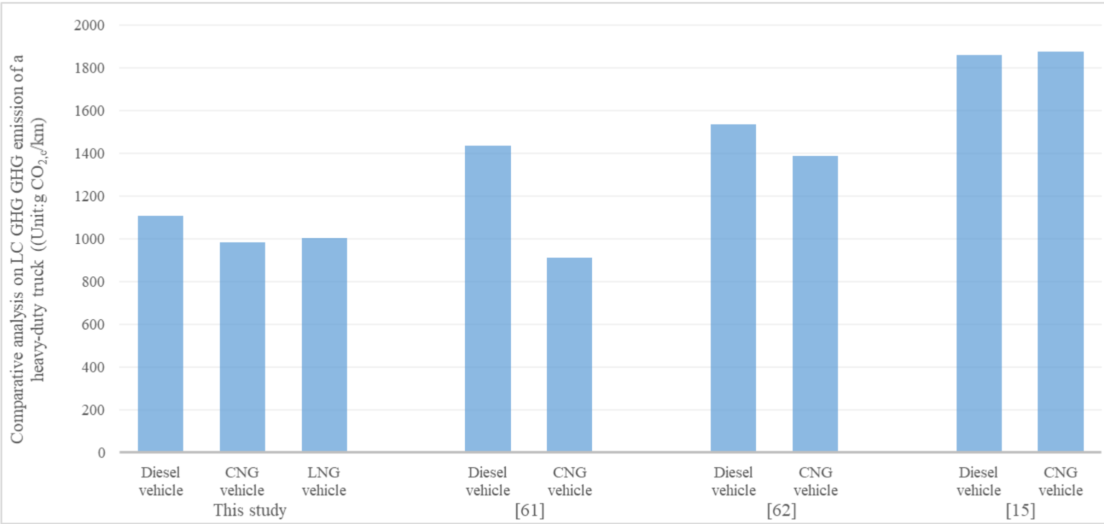

Fig.9. LC GHG emissions of diesel, CNG and LNG heavy-duty trucks in different studies

4.4 Discussions

4.4.1 Sensitivity Analysis of LNG and CNG Pathways

Since energy consumption of fuel transportation for unit distance is relatively insignificant compared to other segments, GHG emission intensities are not sensitive to fuel transportation distances [43]. For CNG and LNG pathways, the major factors influencing LC GHG emissions are processing efficiency, liquefaction proficiency and compressing efficiency.

If NG processing efficiency were assumed to be 90.2%, LC GHG emissions from a private passenger vehicle, a transit bus and a heavy-duty truck fueled by CNG would be 210 g, 873 g and 1,029 g $CO_{2,e}$/km. respectively. As for LNG pathway, LC GHG emissions are 213 g, 886 g and 1,044 g $CO_{2,e}$/km. LC GHG emissions of CNG and LNG vehicles increase by approximately 5% and 4%, respectively. LC GHG emissions of vehicles fueled by NG are still better than traditional gasoline and diesel vehicles. If NG processing efficiency were around 80%, environmental benefits of NG would almost vanish compared to gasoline and diesel.

A large amount of electricity is consumed in the liquefaction process. Therefore, liquefaction efficiency impacts LC GHG emissions heavily. If the liquefaction efficiency were 90%, calculation results for a private passenger vehicle, a transit bus and a heavy-duty truck fueled by LNG yield a LC GHG emissions of 237 g, 985 g and 1,161 g $CO_{2,e}$/km, respectively. Since LC GHG emissions increase by approximately 16%, the environmental benefits of LNG are almost negligible.

If compressing efficiency were 90%, LC GHG emissions of three types of CNG vehicles would be 245 g, 1,200 g and 1,019 g $CO_{2,e}$/km, respectively. Emission results of CNG vehicles increase by 22% and have already exceeded LC GHG emissions results of gasoline and diesel vehicles.

Supposed that vehicle fuel economy of a LNG-fueled private passenger vehicle changes from 13.8 L/100 km to 12.0 L/100 km and vehicle fuel economy of a CNG-fueled private passenger vehicle changes from 8.3 m^3 /100 km to 7.2 m^3/100 km, LC GHG emissions from a private passenger vehicle fueled by CNG and LNG turn out to be 174 and 178 g $CO_{2,e}$/km. Emissions intensities per km are sensitive to vehicle fuel economy, and similar conclusions can be drawn for the other two types of vehicles.

4.4.2 Impact of Natural Gas Vehicle Fleet

Several literatures discussed about the future NGV fleet in China. Peng et al. [49] concluded that NGVs will account for 3.4%, 4.1%, 4.2% and 4.6% of the vehicle stock in China in 2020, 2030, 2040 and 2050, respectively. Hu Ning et al. [63] used a dotted line fitted by NGV stock from 1996 to 2006 to project future NGV stock and the vehicle stock turned out to be 14 million in 2030. Projection for NGV fleet in China is shown in Table 18 based on relevant projections of future NG fleet in China and promulgated policies derived from literature reviews [32, 33, 49, 63-65].

Table 18. NGV stock projection in 2030 and 2050 by vehicle type (Unit: million)

Vehicle type	Fuel type	2030	2050
Private passenger vehicles	CNG	9.77	3.26
Transit buses	LNG	0.11	0.16
Heavy-duty trucks	LNG	0.97	1.58

In 2030, the average annual mileages for a private passenger vehicle, a transit bus and a heavy-duty truck are assumed to be 11.5, 54.6 and 63.9 thousand kilometers, respectively, while in 2050, the annual mileages are assumed to be 9.5, 56.8 and 65.8 thousand kilometers [49], respectively,. Supposed that NGVs are promoted to substitute traditional oil-based vehicles, based on the NGV fleet projection from several scenarios in the previous mentioned studies and the LC GHG emissions estimated in this research, the GHG emission reductions will be about 11.47 and 12.74 million tons in 2030 and 2050, respectively. Overall LC GHG emissions from the on-road transport sector in 2030 and 2050 will be 1937 and 1640 million tons, and NGVs may help reduce LC GHG emissions of on-road vehicles by 0.6% and 0.8%, respectively. Supposed that all the vehicle fleet switch to NGV, overall LC GHG emissions from on-road vehicles will be approximately 1,470 and 1,492 million tons in 2030 and 2050, respectively.

The above emission results indicate that NGVs can be a suitable option for future vehicle fleet in China to help its GHG emissions peak. However, the overall emission reduction effects caused by NGV substitution will not be that distinctive after 2030.

4.4.3 Extension of Life Cycle Analysis to Vehicle Cycle

GHG emissions from material production, transportation, vehicle assemble and recycling are non-negligible. However, the energy consumption and emissions from vehicle cycles in China have not been sufficiently discussed in the previous researches. Hao et al. [66] filled in the gap and estimated the GHG emissions of a standard mid-size private passenger vehicle, and total GHG emission from vehicle production was about 9,597 kg $CO_{2,eq}$ per vehicle. Qiao et al. [67] estimated the GHG emissions from a battery electric vehicle and an internal combustion engine gasoline vehicle (ICEV), and the GHG emissions of producing an ICEV was approximately 9,985 kg $CO_{2,eq}$ per vehicle.

CNG pathway is mostly applied on traditional private passenger vehicles and taxies after retrofitted, and the major difference between CNG vehicles and ICEVs are fuel injection system [65]. Meanwhile, the way of NG storage is the main difference between LNG vehicles and CNG vehicles [65]. Therefore, we assumed that GHG emissions from production of a LNG-fueled vehicle was almost the same as a CNG-fueled vehicle. Vehicle cycle GHG emissions are shown in Table 19 [43, 66-68]. NG-based fuels still enjoy environmental benefits when compared to gasoline vehicles in private passenger vehicles, even though GHG emissions from vehicles are considered.

Table 19. LC GHG emissions of a private passenger vehicle with vehicle cycle taken into consideration (Unit: g/km)

Vehicle type	Fuel type	Vehicle cycle emissions	LC GHG emissions
Private passenger vehicles	Gasoline	49.0	291.3
	CNG	49.5	249.9
	LNG	49.5	254.5

4.4.4 Limitations and Future works

According to several literatures, methane leakages from fuel stations are not insignificant [34, 35, 69]. Cooper et al. [35] took the methane leakages from fuels stations into account, and the methane emissions in CNG and LNG stations were only 0.0004% and 0.00007% of throughput. Clark et al. [69] measured the methane leakages from CNG fuel station compressors, components, and LNG station continuous and nozzle emissions. The results indicated that average leaks of a CNG station and a LNG station are 35.69 and 12.80 g per hour.

The methane leakages from CNG and LNG stations in China have not been fully investigated. Therefore, the methane leakages from the fuel stations are not included into the NG supply chains. Further efforts will be exerted into investigating the methane leakages from the fuel stations and fully cover the LCA system boundary.

It is still controversial whether NGVs can reduce air pollutants or not. Huo et al. [22] found that vehicles fueled by CNG had slightly lower fuel-cycle PM_{10} and $PM_{2.5}$ emissions than traditional gasoline vehicles, and the reduction rate is about 8%. Besides, CNG fueled vehicles can reduce NO_x and SO_2 emissions by 18% and 22%, respectively. Li et al. [68] concluded that NO_x and SO_2 emissions from a CNG vehicle was 33.38% lower than that from a traditional gasoline vehicle, while PM_{10} and $PM_{2.5}$ emissions from a CNG vehicle decreased by 54.22%. Cheng et al. [70] estimated the fuel cycle pollutant emissions from several types of vehicles, and they found NG can achieve 7-38% and 28-42% reduction when compared to gasoline and diesel, respectively.

The LC air pollutant emissions should be further discussed and are highly relevant to the sources of NG and the emissions standards of the vehicles. Different types of air pollutants own different emission characteristics when NG-based fuels are adopted, and LC emissions of several types of air pollutants in NGVs are even more than that in an ICEV. Air pollutant emissions of NG-based fuels require further researches.

5. Concluding Remarks

This paper defines the different natural gas supply chains and different segments involved in each natural gas supply chain and characterizes the contributions of each segment to the total venting and fugitive methane emissions from the natural gas supply chains in China. Four supply chains are taken into consideration, including domestic natural gas, domestic liquefied natural gas, import liquefied natural gas and import pipelined natural gas chains. Segments covered in this paper include production, processing, transportation, distribution, storage, liquefaction and re-gasification. The results indicate that the transportation segment is the largest contributor to the total methane leakages, accounting for 42%-86% of total leakages from these four supply chains. This is followed by the production and distribution segments. The domestic NG supply chain accounts for 67% of the total methane leakages from the NG industry in China.

Based on the analysis of the natural gas supply chain methane leakages and the total output of the NG industry, leakage rates are estimated and used in the life cycle analysis of vehicles. The results show that the Life cycle GHG emissions of private passenger vehicles, transit buses and heavy-duty trucks are lower when NG-based fuels are adopted than those when traditional fuels are used even if methane leakages from NG supply chains are taken into consideration. The emission reductions by the use of CNG and LNG are approximately 11-17% and 9-15%, respectively.

The contribution by methane emissions from NG supply chains to the total life cycle GHG emissions is approximately 2% in 2016. This indicates that methane leakages do not have a significant impact on the total life cycle GHG emissions of a vehicle.

Based on the analysis above, this paper concludes that NG-based fuels perform better in terms of GHG emissions than gasoline and diesel as vehicle fuels in China. In order to reduce GHG emissions from the transport sector, greater efforts in promoting NG-based vehicles to substitute part of the conventional vehicle fleet should be made.

Infrastructures including pipeline networks and fuel stations are the major barriers to natural gas vehicle development in China. Meanwhile, emissions from pipeline networks and fuel stations are considerable. To reduce the GHG emissions from natural gas transportation, which is the major emission contributor in the natural gas supply chain, local governments in the regions with rich natural gas resources should be more active toward natural gas vehicle development in order to reduce the average natural gas transmission distance. Besides, sensitivity analysis in this study indicates that energy consumptions and emissions of compressing and liquefaction processes are highly related to liquefaction and compressing efficiencies. Therefore, energy efficiencies in the fuel station should be further promoted in order to maintain the low-carbon attribute of NG-based fuels from a life cycle perspective.

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Appendix A

Life cycle analysis (LCA) is adopted to assess GHG emissions of NG as fuel in different types of vehicles in terms of functions. LCA is a comprehensive method to evaluate life cycle environmental impacts of different technologies, providing quantitative evidence for policy making. The Tsinghua-LCA Model (TLCAM) is employed to conduct the LCA in this study. TLCAM was developed based on the GREET model with the life-cycle inventory adapted for China. Three primary energies (PE) – coal, NG and oil – and four process fuels (PF) – diesel, gasoline, residue oils and electricity – are taken into account [29,30]. Three types of GHG – CO_2, CH_4 and N_2O – are covered. LC GHG emissions (in CO_2-equivalent) of a specific type of vehicles fueled by LNG, CNG, gasoline and diesel are calculated based on emission of each type of GHG and its global warming potential (GWP), as Eq. (A1) shows.

$$LCGE_r = \left(\sum_{l=1}^{3} (EM_{l,r} \times GWP_l) \right) \times FR \tag{A1}$$

where subscript r represents different fuels used in vehicle, subscript l represents different types of GHG, *LCGE* means the LC GHG emissions (g/km), *EM* denotes emission of CO_2, CH_4 and N_2O (g/MJ), *GWP* means the global warming potential value of different types of GHG and *FR* means the fuel economy (MJ/km).

LC CO_2 emission is estimated by summing up the direct emissions and the upstream emissions of the fuels consumed by vehicles [19,25,26], as Eq. (A2) shows

$$EM_{l,r} = EMD_{l,r} + EMU_{l,r} \tag{A2}$$

Where *EMD* represents the direct combustion emission (g/MJ), *EMU* represents the upstream emissions of production, processing and transportation processes (g/MJ).

The direct emission is calculated through Eq. (A3), based on the carbon balance principle.

$$EMD_{l,r} = \frac{44}{12} \times CC_r \times FOR_r \tag{A3}$$

Where $\frac{44}{12}$ is the conversion ratio between C and CO_2, CC is the carbon content of the specific fuel (g/MJ), and *FOR* is its corresponding oxidation rate.

The upstream emission is obtained by summing up the direct combustion emissions from the process fuels consumed in the production, processing and transportation stages of the vehicle fuel life cycle, as Eq. (A4) shows.

$$EMU_{l,r} = \sum_{m=1}^{4}\sum_{n=1}^{4}\left(EI_{r,m} \times SA_{r,m,n} \times \left(LEFD_{l,r,n} + LEFU_{l,r,n}\right)\right) \tag{A4}$$

Where subscript m means different stages involved in this study, n means the process fuels considered in this study, *EI* means the total energy consumption in the stage m (MJ), *SA* is the proportion that PF n accounts for of the total energy consumption in the stage m, *LEFD* and *LEFU* are the direct and upstream emission factors of the process fuel, respectively (g/MJ).

The direct emission part is derived through the following Eq. (A5).

$$LEFD_{l,r,n} = \frac{44}{12} \times CC_n \times FOR_n \tag{A5}$$

Where $\frac{44}{12}$ is the conversion ratio between C and CO_2, CC is the carbon content of the specific process fuel (g/MJ), *FOR* is its corresponding oxidation rate.

Calculating principles for LC N_2O emission is similar to CO_2 estimation shown in Eq. (A2) and Eq. (A4).

For CH_4 emissions, venting and fugitive methane leakages from the supply chains including production, transportation, processing and liquefaction segments are taken into account, as Eq. (A6) shows.

$$EM_{l,r} = EMD_{l,r} + EMU_{l,r} + \sum_j (LR \times PN) \tag{A6}$$

Where j subscript represents different segments in the NG supply chains, PN means the primary NG consumption in the LC stages and LR is the methane leakage rate based on methane leakages from different segments and the total throughput of the supply chains.

Appendix B

Table B1. Flows of production, processing, transportation and distribution segments in 2008

Segment	Unit	Flows
Production	billion cu.m	76.08
Processing	billion cu.m	73.00
Transportation	billion cu.m	72.00
Distribution	billion cu.m	17.01

Data source: [30]

Table B2. Quantity of facilities in production and transportation segments in 2008

Segment	Facility	Unit	Quantities
Production	Wellhead assembly	set	7100
	Low-pressure and heating NG gathering system	set	460
	Dehydration NG gathering system	set	57
	Metering/ gas distribution system	set	3185
	NG storage station	set	208
Transportation	Compressor/ booster station	set	214
	Metering device	set	619
	Pipeline	set	429
	Pigging station	set	7280

Data source: [30]

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