



Petroleum substitution, greenhouse gas emissions reduction and environmental benefits from the development of natural gas vehicles in China

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Abstract

This study develops a bottom-up model to quantitatively assess the comprehensive effects of replacing traditional petroleum-powered vehicles with natural gas vehicles (NGVs) in China based on an investigation of the direct energy consumption and critical air pollutant (CAP) emission intensity, life-cycle energy use and greenhouse gas (GHG) emission intensity of NGV fleets. The results indicate that, on average, there are no net energy savings from replacing a traditional fuel vehicle with an NGV. Interestingly, an NGV results in significant reductions in direct CAP and life-cycle GHG emissions compared to those of a traditional fuel vehicle, ranging from 61% to 76% and 12% to 29%, respectively. Due to the increasing use of natural gas as a vehicle fuel in China (i.e. approximately 28.2 billion cubic metres of natural gas in 2015), the total petroleum substituted with natural gas was approximately 23.8 million tonnes (Mt), which generated a GHG emission reduction of 16.9 Mt of CO₂ equivalent and a CAP emission reduction of 1.8 Mt in 2015. Given the significant contribution of NGVs, growing the NGV population in 2020 will further increase the petroleum substitution benefits and CAP and GHG emission reduction benefits by approximately 42.5 Mt of petroleum-based fuel, 3.1 Mt of CAPs and 28.0 Mt of GHGs. By 2030, these benefits will reach 81.5 Mt of traditional petroleum fuel, 5.6 Mt of CAPs and 50.5 Mt of GHGs, respectively.

Keywords Natural gas vehicles · Energy use · Greenhouse gases · Critical air pollutants · China · Life-cycle analysis

1 Introduction

As the global economy has prospered, in particular with the economic progress in developing economies, world energy demands have increased significantly in the past few decades. Due to the heavy utilization of fossil energy, dominated by high-carbon and high-pollution energy sources such as coal and oil, enormous quantities of greenhouse gases (GHGs) and critical air pollutants (CAPs) have been

released (International Energy Agency (IEA) 2016; IEA 2015). Moving towards a low-carbon and green economy, many countries are increasing their efforts to reduce GHG and CAP emissions from final demand sectors. As a typical representative of the developing countries and one of the largest economies, China is actively seeking to increase the use of relatively low-carbon and cleaner energy sources such as natural gas (NG) (Ma and Li 2010; National Development and Reform Commission (NDRC) and National Energy Administration (NEA) 2016a, b; Yun et al. 2012). Following the development of an energy revolution strategy, a series of policies and plans have indicated that it is necessary to raise the share of NG in primary energy consumption and to develop natural gas into one of the main energy sources in China (NDRC 2016; NDRC and NEA 2016a, b). Among the final consumption sectors in China, the transportation sector is not only a main contributor to oil consumption but is also a main contributor to GHG and CAP emissions (Yang et al. 2016; Ministry of Environmental Protection (MEP) 2017a).

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Table 1 Overview of policies and plans for both NG and NGV development in China

Time	Item ^a	References
Jun. 2017	The opinions on accelerating the utilization of natural gas	NDRC et al. (2017)
Mar. 2017	The action plan on air pollution prevention and control in the Beijing–Tianjin–Hebei region and the surrounding areas in 2017	MEP et al. (2017)
Jan. 2017	The comprehensive work plan for energy conservation and emission reduction during the 13th Five-Year Plan period	State Council (SC) (2017)
Dec. 2016	The 13th Five-Year Plan for energy development	NDRC and NEA (2016a)
Dec. 2016	The 13th Five-Year Plan for natural gas development	NDRC (2016)
Dec. 2016	The strategy for energy production and consumer revolution (2016–2030)	NDRC and NEA (2016b)
Jun. 2014	The strategy action plan for energy development (2014–2020)	SC (2014)
Sep. 2014	The national plan on climate change (2014–2020)	NDRC (2014)
Sep. 2013	The action plan for air pollution prevention and control	SC (2013)

^aBecause the number of policies and plans issued for both NG and NGV development in China is very high, the key policies and plans issued in the past few years are presented here

Because NG is clean burning and confers power supply advantages, NG fuel is a viable alternative to traditional gasoline/diesel fuel (Hao et al. 2016; Khan et al. 2015; Osorio-Tejada et al. 2015). In recent years, China has increased its efforts to reduce transportation emissions and to reduce the dependence on foreign oil by using NG fuel and by developing natural gas vehicles (NGVs) (see Table 1). Remarkable progress has been made in the development of NGVs in China (see Fig. 1).

Life-cycle analysis (LCA) is a useful modelling tool for quantitatively estimating the energy consumption, environmental emissions and economic effects resulting from the use of alternative fuels and vehicle technologies. Numerous studies have been conducted to investigate the fuel consumption and GHG emissions of alternative vehicle technologies from the life-cycle perspective (Ou et al. 2012; Xu et al. 2015). However, the number of published LCA studies on vehicles using alternative fuels such as NG is relatively small. These studies have focused on LCA studies on NGVs in China from the perspective of alternative fuels, highlighting a wide range of alternatives and analysing fuel pathways (Kliucininkas et al. 2012; Ou and Zhang 2013; Shen et al. 2012). Moreover, most previous studies have conducted an LCA of one or two types of NGVs, such as light-duty passenger vehicles or heavy-duty commercial vehicles (buses or trucks) (Hao et al. 2013; Tu et al. 2013a, b; Ou et al. 2013). Hao et al. (2013) conducted an LCA to estimate the future trends in fuel consumption and life-cycle GHG emissions for on-road trucks in China and emphasized that if the share of liquefied natural gas (LNG) powered trucks in all newly registered semi-trailer towing trucks and heavy-duty trucks is increased to 20% in 2030, an estimated 7.9% and 10.9% of the total diesel consumption by trucks will be replaced by LNG in 2030 and 2050, respectively. In another study, Tu et al. (2013b)

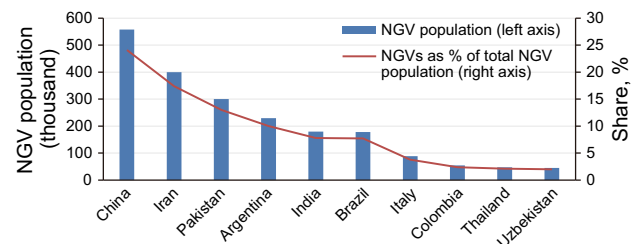


Fig. 1 Countries with the top 10 NGV populations in the world in 2016 *Source:* based on China Automotive Technology and Research Center (CATARC) Beijing Operations (2017), Ma et al. (2013) and NGV Global (2017)

evaluated the life-cycle emissions of GHGs and other pollutants from concrete-mixer trucks (a typical type of trucks) powered by diesel and LNG. The use of LNG was suggested to result in a 9% reduction in GHG emissions compared with diesel, whereas other pollutants varied. As demonstrated by Ou et al. (2013), a life-cycle model is used to assess the GHG emissions of vehicles powered by NG-based fuels and to assess the electric vehicles (EVs) powered with NG-to-electricity in China. From the life-cycle perspective, NG electricity-powered EV and NGV pathways can decrease the life-cycle GHG emissions compared to vehicles powered by petroleum-based gasoline by 42% and 10%, respectively. In addition, few previous studies have focused on the quantitative evaluation of petroleum substitution effects of NGV fleets considering multiple types of NGVs in China (Jiao et al. 2017; Niu et al. 2017). Jiao et al. (2017) constructed a conceptual model of substituting automotive fuels and an evaluation model to investigate the substitutive effects of three kinds of substitutive policies in the Chinese transportation industry: NG, ethanol and methanol. They concluded that these three substitutive policies can significantly reduce the cost of oil dependence, and they suggested that China should promote

an NG alternative policy in the short term. In another study, Niu et al. (2017) evaluated the impact of the development of alternative energy such as gas vehicles, new energy vehicles and biomass fuel on the petroleum demand in China.

Most studies on the CAP emissions of NGVs in China also focus on one or two types of NGVs rather than conducting a comprehensive study on NGV fleets (Rose et al. 2013; Yao et al. 2009). Rose et al. (2013) conducted a comparative LCA of GHGs and other pollutants from heavy-duty refuse collection trucks powered by diesel and compressed natural gas (CNG) in a Canadian city. The authors emphasized that CNG heavy-duty refuse collection trucks can offer an advantage in terms of reduced environmental impacts and cost savings. Another study conducted by Yao et al. (2009) adopted an analytic hierarchy process (AHP) method to perform an evaluation of NGVs (dominated by buses and taxis) in Sichuan Province. The analysis demonstrated that developing NGVs is one of the more effective ways to control oil consumption and air pollution and realize sustainable social and economic development.

Therefore, there is a gap in the knowledge regarding the complete evaluation of petroleum substitution, GHG reduction and CAP reduction benefits of NGV fleets considering the multiple types of NGVs in China. The current study focuses on establishing a bottom-up model to quantitatively assess the comprehensive effect of replacing traditional petroleum-powered vehicles with NGVs in China through an investigation of the direct energy consumption, CAP emissions intensity, life-cycle energy use and GHG emissions intensity of NGV fleets. This study offers four major areas of analysis compared to past studies on NGVs. First, this study establishes a bottom-up model to assess NGVs by considering six segments based on an integrated computing platform. Second, unlike the previous studies, this study adopts real data for key parameters to conduct a systematic and comprehensive analysis of the direct energy consumption, life-cycle energy use, GHG emissions and direct CAP emissions of NGVs. Third, the study explored the comprehensive effects of using NG instead of gasoline or diesel to power vehicles, including the petroleum substitution effect, CAP reduction effect and GHG reduction effect. Fourth, the analysed objects include an NGV and country-level NGV fleets. Finally, a life-cycle fuel inventory database derived from the TLCAM, which is used to conduct the LCA, is specified for the context of China. With these improvements, this study conducts a holistic and comprehensive study on NGVs and comparable traditional fuel vehicles in China by comparing their energy use, GHG emissions and CAP emissions to contribute to decision-making by the government, enterprises and the public.

The aim of this study was to quantitatively assess the comprehensive effects achieved by replacing traditional fuel vehicles with NGVs in China by utilizing actual, reliable data. This information can help identify the potential for expanding the use of NGVs to realize China's targets for the reduction of the dependence on foreign oil and GHG and CAP emissions. The findings of this study will allow decision-makers in countries pursuing low-carbon and sustainable development to make informed decisions when promoting the development of NGVs based on realistic estimations of energy use and environmental emissions. The remainder of article is structured as follows. Section 2 introduces the methods adopted, including the model and the calculation equations. Section 3 mainly describes the assumptions and data adopted for this study. Section 4 presents the results and provides some discussion. Section 5 presents the main conclusions and highlights the key aspects of this work.

2 Methods

2.1 Boundaries

To analyse the energy use and GHG emissions of NGVs in China, a bottom-up calculation method is used on six segments of NGVs with an LCA method using the Tsinghua-LCA Model (TLCAM). The TLCAM was developed by the China Automotive Energy Research Centre, Tsinghua University, and is based on the GREET model, which is a well-known LCA tool (Ou et al. 2013; Ou and Zhang 2013). This model is a Chinese life-cycle modelling tool for evaluating the lifetime energy consumption and GHG emissions of alternative transportation fuels and vehicle technologies. The life-cycle stages of the fuel include energy extraction/transport, fuel production/transport and fuel use. A bottom-up model derived from the TLCAM is developed to investigate the direct energy consumption, life-cycle energy use and GHG emissions for petroleum and NG vehicles in China. In this LCA, C1 denotes the energy extraction sub-stage; C2 is the energy transport sub-stage; C3 is the fuel production sub-stage; C4 is the fuel transport sub-stage; and C5 is the fuel-use sub-stage.

With the help of the iterative and source-tracing functions of the TLCAM, all of the fuels and energy used in the various sub-stages can be converted into the use of three types of primary fossil energy (raw coal, raw NG and petroleum). In this study, GHG emissions include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), which are the most important GHGs. The global warming potential (GWP) in CO₂ equivalents (i.e. CO₂-equivalent (CO_{2,e}) GHG emissions) was calculated assuming a 100-year time horizon (Intergovernmental Panel on

Climate Change (IPCC) 2007; Shahraeeni et al. 2015). According to the Intergovernmental Panel on Climate Change (IPCC) report, the GWPs for CO₂, CH₄ and N₂O are 1, 25 and 298, respectively. For each vehicle type, the model computes the primary energy demand (MJ) and the GHG emissions (g CO_{2,e}).

In addition, the assessment of the CAP emissions intensity of NGVs in China should employ an emission factor method such as that used in Xing et al. (2016) and Yao et al. (2009). In this study, the CAPs include hydrocarbon compounds (HC), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂) and particulate matter (PM, PM_{2.5} specifically). Given the contribution of the vehicle population and CAP emissions, the petroleum-powered vehicles in this study fall under the national standard III (MEP 2017b).

According to investigations and surveys, the largest share of the NGV population in China comprises CNG taxis, other CNG passenger vehicles (PVs), CNG buses, CNG trucks (light duty, LDT), LNG buses and LNG trucks (heavy duty, HDT). Moreover, the majority of CNG trucks are light-duty trucks (LDTs), i.e. CNG LDTs. Most LNG trucks are HDTs, i.e. LNG HDTs. In this study, the NGVs in China include the above six types of vehicles.

2.2 Methodology

This study establishes a bottom-up model to assess the total direct energy consumption and CAP emissions, life-cycle energy use and GHG emissions of on-road diesel/gasoline and NG vehicles in China. The structure of the model is illustrated in Fig. 2.

2.2.1 Fuel consumption calculation of NGV operation and the accompanying petroleum substitution benefit

Based on the fuel consumption rate and annual distance travelled of NGVs in China and the calorific value of each fuel utilized in NGVs, the annual amount of fuel consumed to operate an NGV can be calculated. For the data obtained, the fuel consumption to operate an NGV in China is calculated as in Eq. (1):

$$EC_{i,j} = FE_{i,j} \times ADT_j \times LCV_i \tag{1}$$

where $EC_{i,j}$ is the annual energy consumed to operate an NGV for different applications types in China (MJ); i is the fuel type used in the NGV (see Tables 2 and 3); j is the application type of the NGV ($j = 1, 2, \dots, 4$); $FE_{i,j}$ is the fuel consumption rate of NGVs for different application types (L/100 km); ADT_j is the annual distance travelled by vehicles for different application types (100 km); and LCV_i

is the low calorific value of each type of fuel utilized in NGVs (MJ/L).

By combining the energy consumption of an NGV with the population of NGVs by year, the energy consumed to operate NGVs in China can be calculated. Based on the data obtained, the energy consumed per year by NGV fleets operating in China is calculated as in Eq. (2):

$$EC_{i,t} = \sum_{i=1}^k \left(\sum_{j=1}^k EC_{i,j} \times VP_{i,j,t} \right) \tag{2}$$

where $EC_{i,t}$ is the annual energy consumption of NGV fleets with different application types in China in year t (MJ); k is 2 (when comparing NGVs with gasoline vehicles) or 3 (when comparing NGVs with diesel vehicles); and $VP_{i,j,t}$ is the population of NGVs with different application types in China in year t (thousands). Based on Eq. (2), the accompanying petroleum substitution benefit from replacing traditional fuel vehicles with NGVs in China can be calculated.

2.2.2 Calculating the CAP emissions of NGVs in China

Based on the CAP emissions factors, annual distance travelled and population of NGVs in China, the annual CAP emissions of NGVs can be identified. For the data obtained, the CAP emissions of NGVs in China are calculated as in Eq. (3):

$$CAP_{i,t} = \sum_{i=1}^k \left(\sum_{j=1}^k APEF_{i,j} \times ADT_j \times VP_{i,j,t} \right) \tag{3}$$

where $CAP_{i,t}$ represents the annual CAP emissions of NGVs with different application types operating in China (thousand tonnes) and $APEF_{i,j}$ represents the CAP emission factors of NGVs with different application types operating in China (mg/km). Based on Eq. (3), the CAP emissions reduction benefits from replacing traditional fuel vehicles with NGVs in China can be calculated.

2.2.3 Calculating the energy use of NGVs in China

After the life-cycle primary energy consumption factors for the fuel used in NGVs are determined, the energy use of NGVs in China can be identified. For the data obtained, the life-cycle energy use of an NGV is calculated as in Eq. (4):

$$LCEC_{i,j} = EC_{i,j} \times PECF_i \tag{4}$$

where $LCEC_{i,j}$ is the life-cycle energy consumption of an NGV operating in China with type j application (MJ) and $PECF_i$ is the life-cycle primary energy consumption factor for the fuel life cycle of an NGV using type i fuel (MJ/MJ).

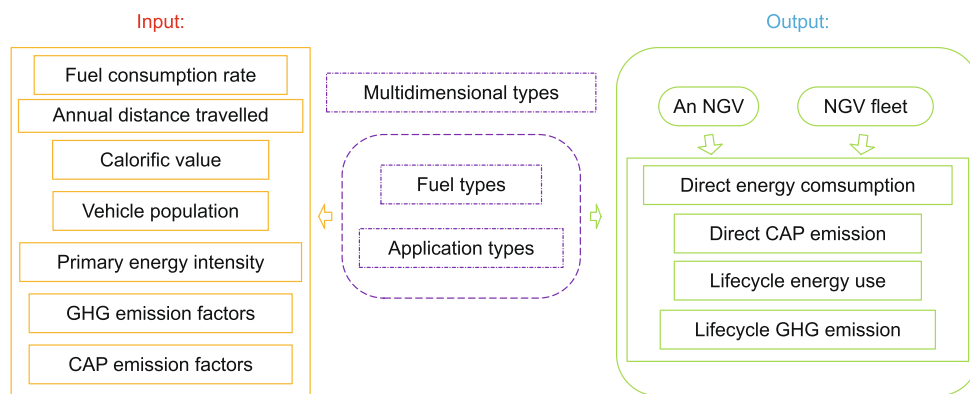


Fig. 2 Diagram of model structure

Table 2 Interpretation of *i* and *j* when comparing NGVs with gasoline vehicles

No.	Fuel type <i>i</i>	Application type <i>j</i>
1	Gasoline	Taxi
2	CNG	Other PVs

Table 3 Interpretation of *i* and *j* when comparing NGVs with diesel vehicles

No.	Fuel type <i>i</i>	Application type <i>j</i>
1	Diesel	Bus
2	CNG ^a	LDT
3	LNG	HDT

^aIn this study, NG trucks include only CNG LDTs and LNG HDTs

Combining Eq. (3) with the population of NGVs per year in China, the energy consumption of NGVs in China per year is calculated as in Eq. (5):

$$LCEC_{i,t} = \sum_{i=1}^k \left(\sum_{j=1}^k LCEC_{i,j} \times VP_{i,j,t} \right) \tag{5}$$

where $LCEC_{i,t}$ is the annual energy consumption of NGVs in China in year *t* (MJ).

2.2.4 Calculating GHG emissions of NGVs in China

Having determined the life-cycle GHG emissions factor for the fuel used in NGVs in China, the GHG emissions can now be investigated. For the data obtained, the life-cycle GHG emissions of an NGV in China are calculated as in Eq. (6):

$$LCGE_{i,j} = EC_{i,j} \times GEF_i \tag{6}$$

where $LCEC_{i,j}$ is the life-cycle GHG emissions of an NGV using type *i* fuel with type *j* application operated in China (g CO_{2,e}); GEF_i is the GHG emissions factor of an NGV using type *i* fuel (g/MJ).

Combining Eq. (5) with the population of NGVs per year in China, the GHG emissions of NGVs in China can be calculated. Based on the data obtained, the GHG emissions of NGVs in China per year are calculated as follows:

$$LCGE_{i,t} = \sum_{i=1}^k \sum_{j=1}^k LCGE_{i,j} \times VP_{i,j,t} \tag{7}$$

where $LCGE_{i,t}$ is the annual GHG emissions of NGVs powered by type *i* fuel for different application types in China in year *t* (g CO_{2,e}). Based on Eq. (7), the GHG emissions reduction benefits from substituting traditional fuel vehicles with NGVs in China can be calculated.

3 Data and assumptions

Seven key data components are required to calculate the desired results of this study: (1) the fuel consumption rate of NGVs in China; (2) the annual distance travelled; (3) the low calorific value of each type of fuel/energy used; (4) the CAP emissions factors of NGVs; (5) the primary energy intensity of the fuel life cycles; (6) the GHG emissions factors of the fuel life cycles; and (7) the population of on-road NGVs.

The primary data used for the evaluation are obtained from real data through a series of investigations and surveys. The data for the fuel consumption rate and CAP emission factors for NGVs in China with different application types are presented in Table 4.

The fuel consumption rate in this study is the specific fuel consumption for NGVs to travel 100 km. The major

Table 4 Fuel consumption rate and CAP emission factors for NGVs. *Source:* based on CATARC Beijing Operations (2017), MEP (2016b), Wang (2015) and Yang and Teng (2018)

Application type	Fuel type	Fuel consumption, L/100 km	Air pollutant emission, mg/km				
			HC	CO	NO _x	SO ₂	PM
Taxi and other PV	Gasoline	8.7	580	5800	210	20	10
	CNG	34.8	266.8	1160	186.9	0 ^a	0.4
Bus	Diesel	32.9	3560	25,330	9600	40	850
	CNG	191.2	1139.2	5825.9	8256	0	27
	LNG	61.3	1139.2	5825.9	8256	0	27
LDT	Diesel	18.7	550	4730	470	20	100
	CNG	108.0	236.5	1040.6	408.9	0	3
HDT	Diesel	36.0	2828	20,107	12,100	40	1071
	LNG	66.3	905	4624.6	10,406	0	30

^aBecause these values are very small, they are assigned a value of zero

Table 5 Major usage characteristics of NGVs in China. *Source:* based on CATARC Beijing Operations (2017), Hao et al. (2015) and Xing et al. (2016)

Annual distance travelled (ADT) (100 km)	CNG Taxi	Other CNG PV	Bus (CNG/LNG)	CNG LDT	LNG HDT
Low ADT	1155	150	627	400	1150
Average ADT	1320	171	726	500	1337.5
High ADT	1485	192	825	600	1525

travel characteristics for NGVs in China are listed in Table 5.

Table 6 shows the primary energy consumption factors and GHG emission factors which can be used to calculate the life-cycle energy use and GHG emissions of NGVs. To investigate the energy consumption and environmental emission of NGV fleets in China, the vehicle population data is also very important. The population of NGVs with different application types in China is displayed in Table 7.

To calculate the fuel use of NGVs in terms of energy, the calorific value of the fuel is required. Different fuels have different calorific values that estimate the energy they contain. Usually, energy is reflected by the calorific value of each fuel. In this study, the calorific values of gasoline, diesel, CNG and LNG fuel are 31.87, 35.83, 7.12 and 21.35 MJ/L, respectively (British Petroleum (BP) 2016; Huo et al. 2012). In addition, the density of gasoline and diesel fuel is 0.74 and 0.84 kg/L (BP 2016; National Bureau of Statistics (NBS) 2016).

4 Results and discussion

4.1 The fuel consumption of NGVs and accompanying petroleum substitution benefit

Figure 3 shows the energy consumption of NGVs in China and that of corresponding traditional fuel vehicles. Given

that the value of the annual distance travelled is a range (see Table 5), the result of annual energy consumption (MJ) by an NGV is also a range. On average, the annual energy consumption of a CNGV is approximately 10.6% lower than that of a comparable gasoline vehicle. However, the annual energy consumption of a CNG/LNG vehicle is on average approximately 13.0% higher than that of a comparable diesel vehicle. In general, the annual energy consumption of an NGV is significantly higher than that of a comparable traditional fuel vehicle. This finding also means that NGV technology needs to be improved to reduce fuel consumption and energy use.

Figure 4 illustrates the petroleum substitution benefit of the use of an NGV in 2015. An NGV results in significant reductions in petroleum consumption compared to the petroleum consumed by a gasoline/diesel vehicle, ranging from 1.2 to 8.9 tonnes and 20.3 to 40.8 tonnes, respectively. The overall NG consumption of NGVs and the amount of traditional fuel being replaced in China in 2015 are presented in Fig. 5. Approximately 28.2 billion cubic metres (m³) of NG were used in the NGV fleet in 2015, serving as a substitute for approximately 23.0 Mt of petroleum-based fuel, which is 7.9% of the petroleum-based fuel consumed in China.

Table 6 Primary energy intensity and GHG emission factors of fuel life cycles in China. *Source:* based on Ou et al. (2012), (2013) and Ou and Zhang et al. (2013)

Types	Gasoline	Diesel	CNG	LNG
Based on the composition of fossil energy				
Fossil energy use, MJ/MJ				
Coal	0.079	0.077	0.08	0.127
Oil	1.159	1.152	0.008	0.015
NG	0.055	0.054	1.124	1.124
Total	1.293	1.283	1.211	1.266
GHG emission, g/MJ				
CO ₂	88.947	92.896	70.560	75.631
CH ₄	0.129	0.052	0.110	0.133
N ₂ O	0 ^a	0.028	0	0
Total	92.17	94.20	73.40	78.95
Based on life-cycle stage				
Fossil energy use, MJ/MJ				
C1 ^b	0.121	0.120	0.125	0.125
C2	0.019	0.019	0.003	0
C3	0.147	0.138	0.084	0.135
C4	0.007	0.007	0	0.007
GHG emission, g/MJ				
C1	9.06	1.53	11.08	0.58
C2	9.00	1.52	10.40	0.58
C3	9.36	0.20	7.42	0.00
C4	9.35	0.00	11.99	0.48

^aBecause these values are very small, they are assigned a value of zero

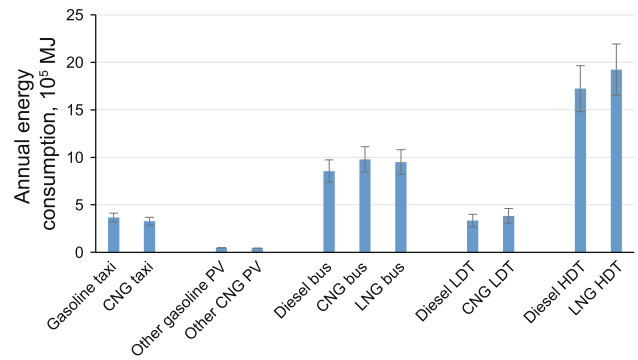
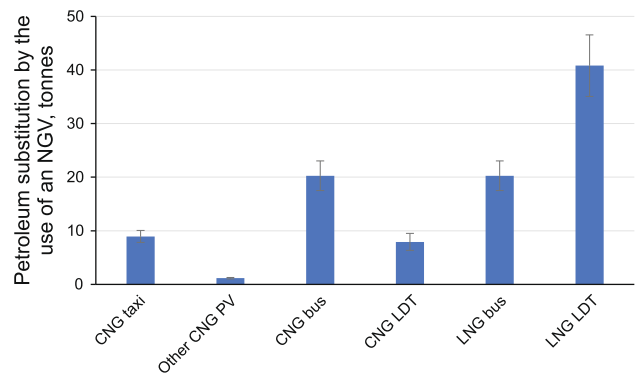
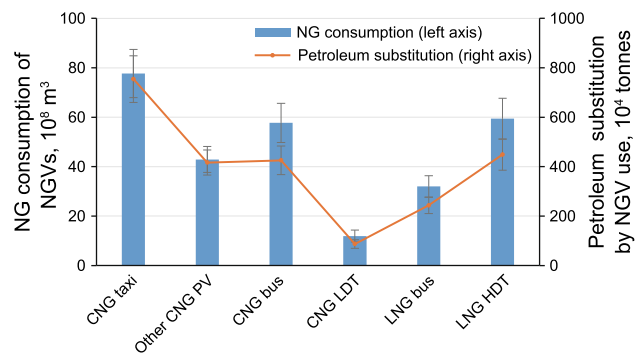
^bC1, C2, C3, C4 and C5 represent the life-cycle sub-stages, i.e. energy extraction, energy transport, fuel production, fuel transport and fuel use

4.2 CAP emissions reduction benefits from increasing the use of NGVs

The estimated annual CAP emissions of NGVs and comparable traditional fuel vehicles in China are illustrated in Fig. 6. Similarly, given that the value of the annual distance travelled is a range, the result of CAP emissions from an NGV is also a range. On average, the emission intensity of a given NGV is distinctly lower than that of a comparable traditional fuel vehicle. In 2015, the CAP emission reduction due to increasing the use of NGVs in China was

Table 7 Classification of the population of NGVs in China by 2015. *Source:* based on CATARC Beijing Operations (2017), China National Petroleum Corporation (CNPC) Economics and Technology Research Institute (ETRI) (2016) and Li (2017)

NGV type	CNG taxi	Other CNG PV	CNG bus	CNG LDT	LNG bus	LNG LDT
Population (thousands)	845	3605	210	110	120	110

**Fig. 3** Direct energy use of NGVs and comparable traditional fuel vehicles in China**Fig. 4** Annual petroleum substitution by the use of an NGV in 2015**Fig. 5** NG consumption of classified NGV fleets and accompanying petroleum substitution in 2015

1.77 Mt, including 0.14 Mt of HC, 1.52 Mt of CO, 0.06 Mt of NO_x, 0.001 Mt of SO₂ and 0.04 Mt of PM (presented in Fig. 7). The biggest contribution of emission reduction

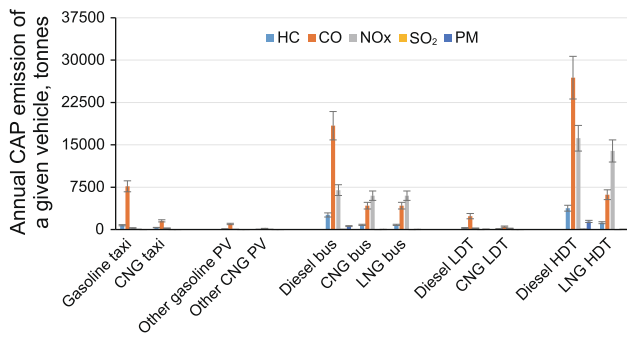


Fig. 6 Annual CAP emission of NGVs and comparable traditional fuel vehicles in China

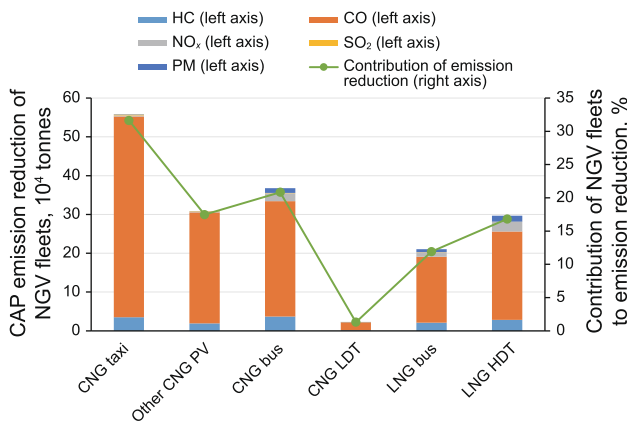


Fig. 7 CAP emissions reduction effect of classified NGV fleets in China

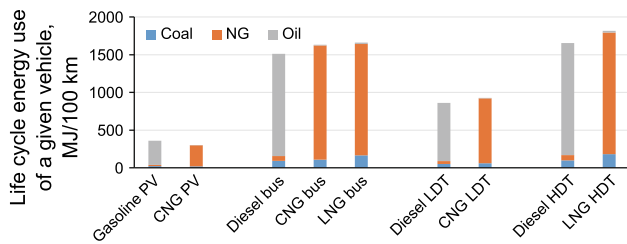


Fig. 8 Life-cycle energy use by primary energy type for NGVs and comparable traditional fuel vehicles in China

generated by classified NGV fleets was from CNG taxis, which resulted in an emissions reduction of 0.56 Mt of CAPs.

4.3 Life-cycle energy use results for NGVs

Figure 8 illustrates the life-cycle primary energy use based on the composition of fossil energy for NGVs and comparable traditional fuel vehicles in China. From a life-cycle perspective, the primary energy use of a given NGV is also comparable to a traditional fuel vehicle. In addition to the

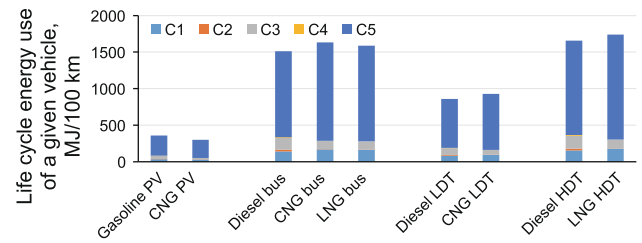


Fig. 9 Life-cycle energy use by life-cycle stages of NGVs and comparable traditional fuel vehicles in China (C1, C2, C3, C4 and C5 represent the life-cycle sub-stages, i.e. energy extraction, energy transport, fuel production, fuel transport and fuel use)

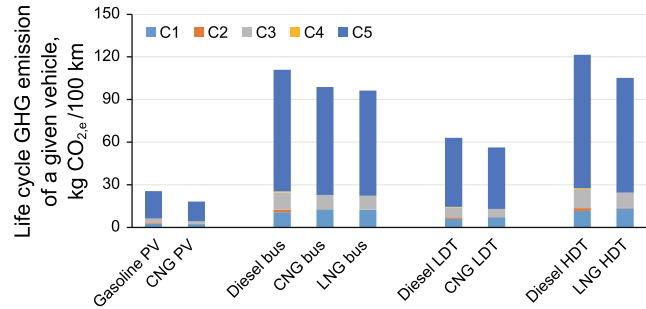


Fig. 10 Life-cycle GHG emissions of NGVs and comparable traditional fuel vehicles in China (C1, C2, C3, C4 and C5 represent the life-cycle sub-stages, i.e. energy extraction, energy transport, fuel production, fuel transport and fuel use)

primary energy use of a given CNGV being significantly lower than that of a comparable gasoline vehicle by approximately of 16.3%, the primary energy use of other NGVs is slightly higher than that of comparable diesel vehicles. Moreover, the results indicate that most of the life-cycle primary energy used is NG for NGVs and oil for traditional fuel vehicles, accounting for 92.7% and 89.6%, respectively. Additionally, it is evident that most of the life-cycle energy use, approximately 77%, occurs during the fuel-use stage for both NGVs and traditional fuel vehicles (see Fig. 9).

4.4 Life-cycle GHG emissions of NGVs and accompanying GHG emissions reduction benefits

Figure 10 illustrates the estimated life-cycle GHG emissions of NGVs and comparable traditional fuel vehicles in China. These results suggest that the life-cycle GHG emissions of a given CNGV are significantly lower than those of a comparable gasoline vehicle. An approximate 29.0% reduction in GHG emissions can be attained in China by replacing a gasoline vehicle with a CNGV. Regarding other types of NGVs, compared to a diesel vehicle, there is also a distinct advantage in GHG emissions with an average of an approximate 12.0% reduction.

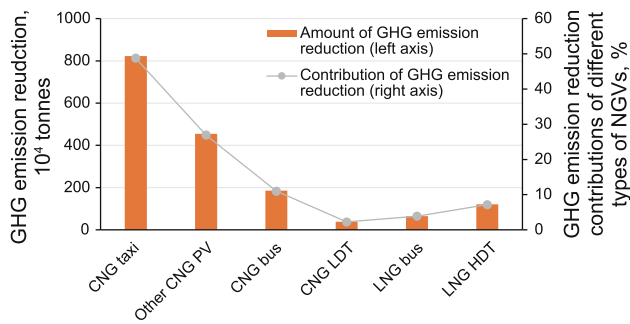


Fig. 11 GHG emissions reduction contributions of classified NGV fleets in China

Moreover, most of the life-cycle GHG emissions, approximately 76%, occur during the fuel-use stage for both NGVs and traditional fuel vehicles. The contribution of classified NGV fleets to GHG emissions reduction in China is presented in Fig. 11. Due to the use of NGVs, the amount of GHG emissions has been significantly reduced. In 2015, the NGV fleet has contributed a GHG emissions reduction of 16.9 Mt of CO₂ equivalent, accounting for approximately 1% of all GHG emissions from on-road vehicles in China (Boden et al. 2016; Energy Information Administration (EIA) of U.S. 2016).

4.5 Comparison of the results with those of other studies

As Table 8 indicates, the LCA energy use results of different studies focused on NGVs in China and other countries are compared. For the LNG HDT and LNG bus application types, this study has a relatively pessimistic result, with net energy saving rate (NESR) values of

−8.4% and −9.5%, respectively, but the NESR values of other studies in China are more optimistic, namely greater than zero (Lin et al. 2015; Tu et al. 2013a). For the CNG LDT application type, the result of this study is −8.6%, a negative result similar to that obtained in other countries such as Canada (Shahraeeni et al. 2015). For the CNG bus application type, among studies specific to China, the current work reports the most optimistic NESR value (Fang 2009; Wang 2015). For the CNG PV application type, all studies (including this study) have similar positive results (Curran et al. 2014; Fang 2009; Ou and Zhang 2013; Wang 2015).

The comparison of the LCA GHG emission results of different studies focused on NGVs in China and other countries is shown in Table 9. For the LNG HDT application type, the value of the net GHG reduction rate (NGRR) in this study is 8%, a positive result similar to that obtained in other studies on China and other countries (Arteconi et al. 2010; Tu et al. 2013b). For the LNG bus application type, the result in this study is 7%, a more pessimistic result than that of other studies specific to China but similar to the findings of studies from other countries (Beer et al. 2002; Ercan and Tatari 2015; Lin et al. 2015). For the CNG LDT application type, the result of this study is 10.4%, which is a more pessimistic result than that obtained for Canada (Shahraeeni et al. 2015). For the CNG bus application type, all studies (including this study) have similar positive results (Beer et al. 2002; Ercan and Tatari 2015; Fang 2009; Wang 2015; Xu et al. 2015). For the CNG PV application type, the studies specific to China (including this study) have similar NGRR figures, but they have a more optimistic result than that found for

Table 8 NGVs' LCA energy use results across studies

NGV type	Region	Source	Press time	Net energy saving rate, %
LNG HDT	China	This study	2017	−8.4
	China	Tu et al. (2013a)	2013	6.4
CNG LDT	China	This study	2017	−8.6
	Canada	Shahraeeni et al. (2015)	2015	−2
LNG Bus	China	This study	2017	−9.5
	China	Lin et al. (2015)	2015	7.9
CNG Bus	China	This study	2017	−9
	China	Wang (2015)	2015	−26
	China	Fang (2009)	2009	−14.6
CNG PV	China	This study	2017	16.3
	China	Ou and Zhang (2013)	2013	1.9
	China	Wang (2015)	2015	23
	China	Fang (2009)	2009	−8.3 to 9 ^a
	USA	Curran et al. (2014)	2014	23

^aCNG PV in Fang (2009) includes CNG/gasoline-fuelled PV and CNG-fuelled PV

Table 9 NGVs’ LCA GHG emission results across studies

NGV type	Region	Source	Press time	Net GHG reduction rate, %
LNG HDT	China	This study	2017	8
	China	Tu et al. (2013b)	2013	8.9
	Europe	Arteconi et al. (2010)	2010	10
CNG LDT	China	This study	2017	10.4
	Canada	Shahraeeni et al. (2015)	2015	34
LNG Bus	China	This study	2017	7
	China	Lin et al. (2015)	2015	18.3
	USA	Ercan and Tatari (2015)	2015	7.8
	Australia	Beer et al. (2002)	2002	4.9
CNG Bus	China	This study	2017	10
	China	Wang (2015)	2015	8
	China	Fang (2009)	2009	11.4
	USA	Xu et al. (2015)	2015	24
	USA	Ercan and Tatari (2015)	2015	8.4
	Australia	Beer et al. (2002)	2002	9.8
CNG PV	China	This study	2017	28.8
	China	Ou and Zhang (2013)	2013	10–20
	China	Wang (2015)	2015	42
	China	Fang (2009)	2009	10.7–26 ^a
	USA	Curran et al. (2014)	2014	20.4

^aCNG PV in Fang (2009) includes CNG/gasoline-fuelled PV and CNG-fuelled PV

the USA (Curran et al. 2014; Fang 2009; Ou and Zhang 2013; Wang 2015).

Differences between life-cycle energy use and GHG emissions results among studies of NGVs in China and other countries are largely due to (1) the difference in the adopted fuel consumption rate, including the impact of different application types and tonnage types. For example, a study by Tu et al. (2013b) evaluated the life-cycle emissions of GHGs and other pollutants from NG-powered concrete-mixer trucks, a typical type of truck (Cai et al. 2017; Hao et al. 2015; Song et al. 2017; Tu et al. 2013b); (2) differences in the energy consumption and GHG emissions produced in the process of fuel acquisition, particularly for widely used industry boilers largely fuelled by coal, which have a low efficiency compared with the global level (Cai et al. 2017; Ou et al. 2010; Wang 2015); and (3) different operating environments (Ercan and Tatari 2015; Lajunen and Lipman 2016; Lin et al. 2015).

4.6 Enhancing the petroleum substitution, greenhouse gas emissions reduction and environmental benefits by increasing the use of NGVs

If given increased attention from the Chinese government, for example, increasing the efforts to address the pollution from diesel HDTs in the Beijing–Tianjin–Hebei region

beginning in 2017 (MEP et al. 2017; NEA et al. 2017), NGVs have a promising future. Based on the issued policies and plans, it is estimated that the population of NGVs in 2020 and 2030 in China will be 8 and 14 million, respectively (CATARC Beijing Operations 2017; Li 2017; NDRC 2016). Accordingly, the accompanying petroleum substitution benefits and CAP and GHG emissions reduction benefits from NGV use in 2020 and 2030 in China are presented in Figs. 12, 13, 14. The NG consumption of NGVs in 2020 and 2030 in China is estimated to be 51.1 and 99.1 billion m³, respectively. In 2020, the accompanying petroleum substitution benefits and CAP and GHG emissions reduction benefits from increasing the use of NGVs in China will be 42.5 Mt of petroleum-based fuel, 3.1 Mt of CAPs and 28.0 Mt of GHGs, respectively. By 2030, 81.5 Mt of traditional petroleum fuel will be reduced, and an emissions reduction of 5.6 Mt of CAPs and 50.5 Mt of GHGs will be achieved.

5 Concluding remarks

This study develops a bottom-up model for NGV fleets in China and conducts an LCA with a combination of real-time fuel economy data, actual vehicle population data and a life-cycle inventory database from the TLCAM specified for the context of China. A comparative study on the direct

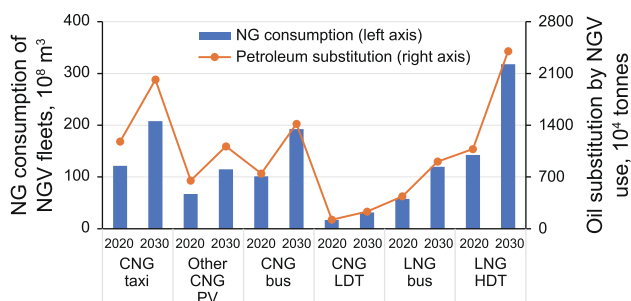


Fig. 12 NG consumption of classified NGV fleets and accompanying petroleum substitution in 2020 and 2030

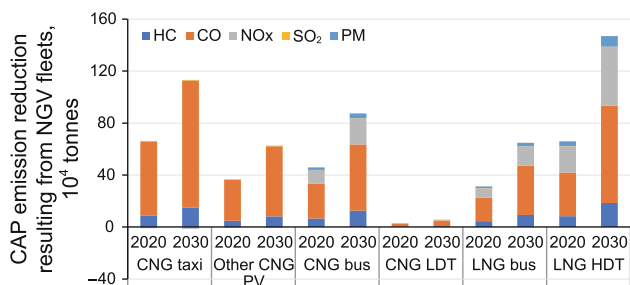


Fig. 13 CAP emission reduction resulting from classified NGV fleets in 2020 and 2030

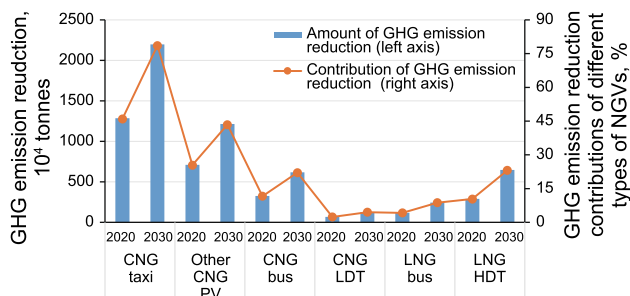


Fig. 14 GHG emissions reduction contributions of classified NGV fleets in China in 2020 and 2030

energy consumption, life-cycle energy use, direct CAP emissions and life-cycle GHG emissions intensity of NGVs and comparable traditional fuel vehicles in China is conducted. Based on this analysis, the comprehensive effects of replacing traditional petroleum fuel powered vehicles with NGVs in China, including the petroleum substitution benefit, CAP reduction benefit and GHG reduction benefit, are investigated.

Our findings indicate that on average, there are no net energy savings from replacing a traditional fuel vehicle with an NGV. Therefore, appropriate measures need to be taken to improve transportation system efficiency based on the resources consumed. Interestingly, an NG-powered vehicle results in significant direct CAP and life-cycle GHG emissions reductions compared to that of a traditional

fuel vehicle, ranging from 61% to 76% and ranging from 12% to 29%, respectively. An NGV results in significant reductions in petroleum consumption compared to a gasoline/diesel vehicle, ranging from 1.2 to 8.9 tonnes and 20.3–40.8 tonnes, respectively. Due to the increasing use of natural gas as a vehicle fuel in China (i.e. approximately 28.2 billion cubic metres of natural gas in 2015), the total gasoline/diesel fuel substituted with natural gas was approximately 23.8 Mt, which generated a GHG emissions reduction of 16.9 Mt of CO₂ equivalent and a CAP emissions reduction of 1.8 Mt in 2015. Given the significant contribution of NGVs, growing the NGV population in 2020 will further increase the petroleum substitution benefits and CAP and GHG emissions reduction benefits by approximately 3.1 Mt of CAPs and 28.0 Mt of GHGs, respectively. By 2030, these benefits will reach 81.5 Mt of traditional fuel, 5.6 Mt of CAPs and 50.5 Mt of GHGs, representing a significant contribution to energy security and emissions reduction for China. Therefore, China should increase its efforts to promote the use of NGVs to replace traditional fuel vehicles.

Because the use of NGVs contributes significantly to reducing CAP and GHG emissions, increasing the share of NGVs in the vehicle market can play an important role in improving air quality and addressing climate change. To achieve this target, potential solutions should be developed by considering three perspectives: NGV enterprises, governmental departments and public consumers. NGV enterprises should enhance the research and development of NGVs. Consistent development will not only increase the energy economy of the produced vehicles but will also improve their quality. This progress will further reduce pollutant emissions, reduce maintenance costs and even reduce purchase and modification costs. To accelerate the development of NGVs, governmental departments must provide effective policy support in terms of making NG prices competitive with petroleum-based fuel prices, promoting NG infrastructure construction, providing purchase subsidies, offering highway fee concessions and enhancing the environmental requirements of NGVs (Li et al. 2015; Wu et al. 2016; Zheng et al. 2015). Moreover, to better stimulate the development of NGVs, different countermeasures need to be implemented that take into account the different circumstances in different provinces (CATARC Beijing Operations 2017). Furthermore, increasing the awareness of public consumers regarding the positive environmental impacts and the cost-effectiveness of NGVs compared to traditional fuel vehicles is very important. If more consumers understand that NGVs are affordable and environmentally friendly, more NGVs will be sold, which will increase the use of NGVs.

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