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Article

Life Cycle GHG of NG-Based Fuel and Electric Vehicle in China

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Abstract: This paper compares the greenhouse gas (GHG) emissions of natural gas (NG)- based fuels to the GHG emissions of electric vehicles (EVs) powered with NG-to-electricity in China. A life-cycle model is used to account for full fuel cycle and use-phase emissions, as well as vehicle cycle and battery manufacturing. The reduction of life-cycle GHG emissions of EVs charged by electricity generated from NG, without utilizing carbon dioxide capture and storage (CCS) technology can be 36%–47% when compared to gasoline vehicles. The large range change in emissions reduction potential is driven by the different generation technologies that could in the future be used to generate electricity in China. When CCS is employed in power plants, the GHG emission reductions increase to about 71%–73% compared to gasoline vehicles. It is found that compressed NG (CNG) and liquefied NG (LNG) fuels can save about 10% of carbon as compared to gasoline vehicles. However, gas-to-liquid (GTL) fuel made through the Fischer-Tropsch method will likely lead to a life-cycle GHG emissions increase, potentially 3%–15% higher than gasoline, but roughly equal to petroleum-based diesel. When CCS is utilized, the GTL fueled vehicles emit roughly equal GHG emissions to petroleum-based diesel fuel high-efficient hybrid electric vehicle from the life-cycle perspective.

Keywords: NG-based fuel; vehicle; GHG; life cycle analysis; China

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1. Introduction

1.1. Natural Gas: A Thriving Energy Resource in China

China does not have large domestic reserves of oil or natural gas (NG), and their proven recoverable reserves are 0.9% and 1.5% of the World total, respectively [1], while China is currently the largest energy producer and consumer in the World [2]. In 2011, China consumed 1.839 Btoe of coal, ranking number one in the World (49.4% of the World total). This year China consumed 461.8 Mtoe of oil and 117.6 Mtoe of NG, which are 11.4% and 4.0% of the World total, respectively [1].

The percentage of coal in China's total primary energy consumption was 68.8% and coal is expected to play a crucial role as an abundant energy source in China for the long term [3]. However, both clean and advanced coal technologies are needed to utilize coal in an environmentally responsible manner while improving utilization efficiency [4].

Though the share of NG in China's total energy consumption was very low in the past years (2.6% in 2001 and 4.6% in 2011), the rates of increase were significant: the average annual rate of increase was 13% and 16%, respectively, for NG production and consumption in China in the period from 2001 to 2011 [5].

It is stated that intensified efforts will be made in the prospecting and exploitation of both conventional and non-conventional oil and gas resources in the white paper titled "China's Energy Policy 2012", though the availability of domestic gas resources are overestimated by China's authorities [6]. China aims to increase the share of NG in China's total energy consumption to 7%–8% by 2015, according to the specific plan for NG development in China (2011–2015) [5,7]. It is estimated that share of NG in China's total energy consumption can reach to 13% and 15% by 2030 and 2050, respectively [8], by expanding the domestic production and international imports at the same time.

1.2. Transport Sector: Fast-Growing and Looking for Solutions to Oil Supply Security

China has become the number one producer and market for automobiles for the first time in 2009 and has remained in this position since then. The new sales of highway vehicle were over 18 million in 2011 and the highway vehicle population was 94 million at the end of 2011 [9].

Oil demand in China is increasing with significant growth in highway transport infrastructure accompanied by the dramatic growth in car usage [10]. However, the slow growth of China's domestic oil supply has increased its dependency on imported oil and this ratio has risen to about 56% as of 2011 [1,3]. The number of vehicles in China is estimated to increase to about 588 million in 2050 from 80 million vehicles in 2010. By 2050, these vehicles will consume 539 Mtoe and emit 1650 Mt CO_2 per year in the Reference Scenario [11].

To curb oil demand, the Chinese government is making great efforts by regulating vehicle fuel economy and introducing alternative fuels, including NG-, biomass- and coal-based fuels [12–16]. There is a consensus that it is increasingly important for China to reduce its GHG emissions and it is publicly recognized that low-carbon or climate-friendly energy policies should align with and support corresponding activities such as applying CO_2 capture and storage (CCS) technologies [17].

1.3. NG-Based Fuel and EVs: Transportation Fuel Options for China

Compressed NG (CNG) and liquefied NG (LNG), which are in the commercialization stages, are currently encouraged as supplies for vehicle use in China, while the scale of gas-to-liquid (GTL), which is in the demonstration stage, is also suggested to expand [18].

CNG is stored in high-pressure tanks, where the pressure is around 20 MPa. CNG vehicle engines can be considered mature after several generations of technological advances. CNG refueling stations can be integrated into existing petroleum stations or built singly [11].

Unlike CNG, which needs to be stored at high pressure, LNG can be stored and transported at atmospheric pressure and −162 °C. LNG vaporizes with the higher temperature inside a vehicle. This allowed specialized LNG vehicles to be developed. The volume of liquid LNG is only one-third that of CNG for the same weight, which greatly increases the energy density of this form of natural gas. Therefore, compared with CNG vehicles, LNG vehicles can significantly reduce the size and weight of the vehicle fuel system, the number of refueling stops, and improve the vehicle range. LNG is thus especially suitable for fixed-line, long-distance, heavy vehicles. The development of LNG vehicles demands the installation of LNG filling stations or small-scale natural gas liquefaction equipment at CNG filling stations [11].

GTL can be produced in two ways—direct and indirect synthesis. The latter process is more technically mature, and it consists of three parts—gas production, Fischer-Tropsch synthesis, and product refinement. Though GTL fuel (with a composition close to diesel) is very high in quality and very low in sulfur content, and does not entail any changes to conventional vehicles, its immature production technology indicates that that it can be commercialized by 2030 [11].

Finally, EVs are also proposed in China as a transportation fuel solution and long-term strategies are being discussed to commercialize EVs as well as plug-in hybrid vehicles (PHEVs) [19–21].

Thermal power plays the dominant role in China's electricity sector with the share of 82.5% in total power generation and 72.5% in total power capacity in 2011 [3]. Coal-fired power plants accounted for about 92% of the total thermal power capacity in 2010 [22]. In recent years, the Chinese government has encouraged increasing the NG-fired power share in the power sector: 2.90% in 2015, 3.50 in 2020, 3.1% in 2030 and 4.1% in 2050 [23]. The NG for power generation was 4.1% of total NG in 2000, and 10.8% in 2008, but could be as high as 22% in 2030 and 2050 [8].

1.4. Lifecycle GHG Analysis: Hot Issue for Transportation Fuels from NG

Life cycle GHG emissions have become critical and necessary information influencing the implementation of appropriate energy policies in a GHG constrained world. Many researchers have made great efforts to understand the total impact of GHG Well-to-Wheels (WTW) life cycle analysis (LCA) of the NG-based fuel and electricity supply chains.

LCA studies comparing NG-based fuel for vehicles to gasoline and diesel vehicles have reached different conclusions, partially due to the use of locale-specific data. Comparing CNG and diesel light duty vehicles, Weiss *et al*. [24,25] have done an LCA study showing higher efficiency and reduction of CO_2 emissions for CNG compared to gasoline.

Some previous studies on comparative LCAs of heavy duty CNG and diesel vehicles were focused on transit buses [26–29]. Among them, Karman [27] found significant reductions of CO_2 emissions for vehicles in the city of Beijing, China, when switching to CNG, but stressed the importance of locale-specific data for an LCA, while Ally and Pryor [26] stated that a CNG bus can emit a little more than a diesel bus in Australia's real situation.

Rose *et al.* [30] concluded that a 24% reduction of (CO_2-equivalent) GHG emissions may be realized by switching from diesel to CNG for refuse collection vehicles based on the real-time operational data obtained from the City of Surrey in British Columbia, Canada. Shen *et al.* [31] also found the CNG vehicles can reduce GHG by 14%–19%hen compared to a gasoline vehicle in the period of 2010–2020 under China's road conditions.

Arteconi *et al.* [32] found the LNG purchased directly from the regasification terminal enables a 10% reduction in GHG emissions in comparison with diesel, while the emissions produced locally (at the service station) with small-scale plants are comparable with those of diesel in Europe. On the other hand, in the 2008 CARB study [33] referred in [32], it is stated that there was no advantage for the use of LNG in terms of GHG emissions in comparison with diesel: GHG emissions of LNG fuelled heavy-duty vehicles were 6.4% higher than diesel emissions in the USA.

Van Vliet *et al*. [34] found that, without CCS, even GTL is found to cause up to 10% higher GHG emissions than fossil diesel, but it is also concluded that in the future, highly efficient conversion plants with CCS could give GTL a slight advantage over oil-derived fuels, reducing emissions by 5% *vs*. fossil diesel. Weiss *et al*. [24,25] also found GTL will produce an increase in energy demand which offsets any GHG reduction in vehicle usage. These conclusions are line with [18] where the life cycle energy consumption and GHG emissions of GTL fuel are 27.3%–74.2% and 7.4%–27.3% higher than for diesel under China's conditions.

There is no comprehensive and in-depth LCA study for multiple NG-to-fuel pathways in China's context. For the LCA of NG-to-electricity, Weisser [35] made an overview on GHG LCA of global generation pathways. This study is helpful in giving a general picture, but lacks country-specific indices. Some analysis including the life cycle of electricity generation, transmissions and distribution in China date back to 2002 [36,37], covering only thermal power as a whole or coal-based power. Specific LCA studies for NG-to-electricity pathways are also scarce.

1.5. The Purpose of this Paper

The purpose of this paper was to compare in-depth NG-based fuel used as the vehicle fuel through multiple pathways. We focused on the GHG emissions throughout the life cycle of the fuels, considering various procurement scenarios for fuel production (*i.e.*, LNG liquefied in central terminal or produced locally at the service station), so in this paper, a comparison of the life cycle GHG emissions is conducted for: (1) three pathways of NG-based fuels (CNG, LNG and GTL); (2) two pathways of NG-based electricity for EVs; and (3) two pathways of petroleum-based fuels (gasoline and diesel).

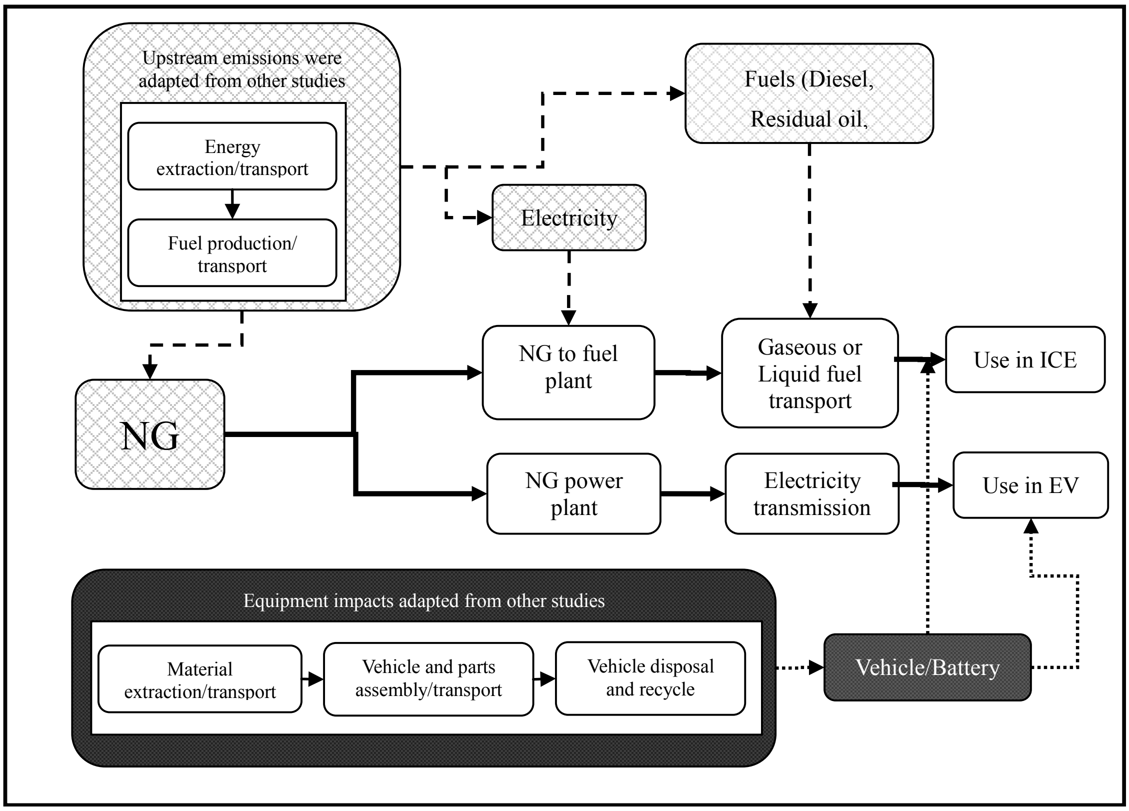
The following sections introduce the boundaries and methodology adopted for this study, the assumptions and lists the data for specific pathways and vehicle use, and a summary of the results, discussion and conclusions.

2. Methodology

2.1. System Boundary and Functional Units

The Tsinghua-LCA Model (TLCAM) [38,39] is employed to compare the life cycle GHG emissions of NG-based fuels, NG-to-electricity for EVs and petroleum-based fuels utilized in vehicles of the same platform. The life cycle stages for each of the fuels included starts with the extraction of the NG and ends with the use of the fuels in the vehicle, as shown in the system boundary description (see Figure 1). The life cycle stages of the vehicle and battery manufacturing are also included, covering extraction/transport, to vehicle and parts manufacturing, and vehicle disposal and recycling.

Figure 1. System boundary of included process.



With the help of the iterative and source-tracing function of the TLCAM, all the fuels and energy used in all various sub-stages can be converted to the use of three types of primary fossil energy (raw coal, raw natural gas and petroleum).

These upstream emissions can be found in Li *et al*. [39] and the emissions associated with coal extraction, transport and CH_4 leakage from coal mine are assessed. Three key types of GHG emissions (CO_2, CH_4 and N_2O) are taken into consideration and the global warming potentials for $CO_{2,e}$ were calculated assuming a 100-year time horizon [40].

The final functional unit is that of vehicle distance. And therefore for each vehicle type the model computes primary energy demand (MJ per km), and the GHG emissions (g CO_2, e per km).

2.2. Calculation Methods for NG-Based Fuels and NG-to-Electricity

The model calculates the life cycle energy for the NG-based fuels pathway used as the sum of the original three types of primary fossil energy consumed for the process energy used in the NG-based fuels plants and the fuel consumption for NG-based fuels transport. For the NG-to-electricity pathways, the life cycle energy used is calculated as the original three types of primary fossil energy consumed for the cleaned NG used in the power plant. For both NG-based fuels and NG-to-electricity pathways, the life cycle GHG emissions are calculated as the sum of both the upstream emissions and the direct emissions intensity for the process energy and transportation fuel used throughout each of the sub-stages:

2.2.1. Calculation Methods for Life Cycle Energy Use and GHG Emissions

We define E_{LC} as the life cycle of PE (primary fossil energy) consumption (MJ/MJ fuel or electricity), i as the type of primary fossil energy (PE) (coal, natural gas and petroleum), j as the type of process fuel (PF) used in this study (electricity, diesel, residual oil, gasoline) and $EF_{LC,j,i}$ as the life cycle primary energy intensity representing the amount of PE type i consumed in order to obtain 1 MJ PF type j (MJ/MJ). To define the specific NG-based fuels pathway, the life cycle energy used is calculated on the basis of process energy used in the plants plus the fuel consumption for liquid fuel transport:

$$E_{LC} = \sum_{i=1}^{3}(EN_{plant,NG}EF_{LC,NG,i} + EN_{plant,electricity}EF_{LC,elecricity,i} + \sum_{j=1}^{4}(EN_{transport,j}EF_{LC,j,i})) \quad (1)$$

in which:

$$EN_{plant,NG} = SH_{plant,NG} / \eta_{plant} \quad (2)$$

$$EN_{plant,electricity} = (1 - SH_{plant,NG}) / \eta_{plant} \quad (3)$$

where, $EN_{plant,NG}$ is the amount of NG used in the plant per MJ of final fuel obtained (MJ/MJ fuel); $EN_{plant,electricity}$ is the amount of electricity used in the plant per MJ of final fuel obtained (MJ/MJ fuel); $EN_{transport,j}$ is the amount of PF j used during the process of NG-based fuels transport for 1 MJ of fuel (MJ/MJ fuel); $SH_{plant,NG}$ is the share of NG in the total energy input for NG-based fuels production; and η_{plant} is the energy efficiency of NG-based fuels for a NG-based power plant.

For NG-based electricity pathways, it is simpler to calculate life cycle results because only one type of PF (NG) is used:

$$E_{LC} = \sum_{i=1}^{3} EN_{plant,NG}EF_{LC,NG,i} \quad (4)$$

$$EN_{plant,NG} = 1 / (\eta_{plant}(1 - R_{trans})) \quad (5)$$

where R_{trans} is the loss rate during electricity transmissions.

2.2.2. Calculation Methods for Life Cycle GHG Emissions

GHG_{LC} (LC GHG emissions) for this calculation includes the three primary types of GHG emissions (CO_2, CH_4 and N_2O) emitted during the life cycle process. Each of the GHG emissions is then converted to CO_2 equivalents ($CO_{2,e}$) according to their global warming potential (GWP) value:

$$GHG_{LC} = CO_{2,LC} + 23CH_{4,LC} + 296N_2O_{LC} \tag{6}$$

The life cycle emissions of each specific type GHG can be calculated by the sum of both the upstream emissions and the direct emissions intensity of the PF used (EN) throughout the process.

Therefore, below is an example of the CO_2 emissions induced by NG utilization in the plant:

$$CO_{2,plant,coal} = EN_{plant,NG}(CO_{2,up,NG} + CO_{2,direct}) \tag{7}$$

$$CO_{2,direct} = \frac{44}{12}CC_{NG}FOR_{NG} \tag{8}$$

where $CO_{2,up,NG}$ is the upstream CO_2 emission factor of NG (g/MJ); $CO_{2,direct}$ is the direct CO_2 emission factor of NG used as process fuel (g/MJ); CC_{NG} is the carbon content of NG (g/MJ) and FOR_{NG} is the carbon oxygenated rate of NG.

Similarly, $CH_{4,up}$ and N_2O_{up} are defined as upstream emissions factors (g/MJ); and $CH_{4,direct}$ and N_2O_{direct} are defined as direct emissions factors (g/MJ).

2.3. Fuel/Vehicle Combination

We define the life cycle impacts from fuel per each km driven by multiplying vehicle energy efficiency (MJ/km) by the life cycle energy used to determine the resulting GHG emissions for each NG-based fuels and NG-to-electricity fuel pathway. By further adding the energy use and GHG emissions, per vehicle km driven, for the corresponding battery and other auxiliary impacts, the final life cycle results for fuel/vehicle combination pathways are determined.

3. Data and Assumption

3.1. Life Cycle Energy Intensity and GHG Emission Factors of Process Fuels

The data on life cycle primary energy intensity are taken from [39] and listed in Table 1. For example, 1 MJ of NG used for process energy, requires 0.04 MJ of raw coal, 1.06 MJ of raw natural gas and 0.05 MJ of petroleum during the entire life cycle stages, which include raw NG extraction and processing, and transportation to the end-use location.

The data on upstream and direct GHG emission factors of process fuels are also taken from [39] and listed in Table 2. Here we can see that to use 1 MJ of diesel for process energy, for example, results in 19.4 g of CO_2, 0.04 g of CH_4 and 0.48 mg N_2O emitted during the upstream life cycle stages, which include crude oil extraction and processing, transportation, oil refining, and diesel used for transportation to the end-use location. The same 1 MJ of diesel will emit 72.6 g of CO_2, 0.004 g of CH_4 and 0.002 mg N_2O of direct emissions when combusted for transportation fuel.

Table 1. Life cycle primary energy intensity for process energy in China.

Process energy	Life cycle intensity		
	Raw coal	Raw NG	Petroleum
	MJ/MJ	MJ/MJ	MJ/MJ
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
Residual oil	0.06	0.06	1.11
Electricity	2.3	0.18	0.07

Table 2. Life cycle upstream and direct emission factors for secondary energy in China.

Process energy	Upstream CO_2	Upstream CH_4	Upstream N_2O	Direct CO_2	Direct CH_4	Direct N_2O
	g/MJ	g/MJ	mg/MJ	g/MJ	g/MJ	mg/MJ
Coal	7.3	0.44	0.39	81.6	0.001	0.001
NG	10.4	0.09	0.42	57.0	0.001	0.001
Diesel	19.4	0.04	0.48	72.6	0.004	0.002
Gasoline	20.2	0.05	0.49	67.9	0.080	0.002
Residual oil	16.6	0.04	0.45	75.8	0.002	0
Electricity	203.6	0.95	3.23	0	0	0

3.2. NG-Based Fuels Pathways

Plant energy efficiency data vary not only from each other in pathway technologies, but also in different capacity-size or installed-time, as Table 3 shows.

Table 3. Energy efficiency situations of each NG-based fuel pathway.

Pathway	Time	Plant energy efficiency (LHV)/%	Note
CNG	Current	96.9%	Based on the investigation by AERT (2006) [41], CATARC and GM (2007) [42] and CAERC (2012) [11].
	Future	97.3%	Prediction by CAERC (2012) [11].
LNG	Current	95.2% (Electricity as major fuel)	Based on the investigation by CATARC and GM (2007) [42] and CAERC (2012) [11].
	Future	90.2% (NG as major fuel)	Prediction by CAERC (2012) [11].
GTL	Current	54.2%	Based on the investigation by CATARC and GM (2007) [42] and CAERC (2012) [11].
	Future	63%	Prediction by Hao *et al*. (2010) [18].

The data regarding process fuel mix and fuel transportation mode are listed in Table 4 according to [39]. For CNG, the process fuel mix in the plant is 3% of NG and 97% of electricity, which is assumed to be supplied by the public electricity grid. It is then transported to the end user by road vehicle over an average distance of 50 km. For LNG pathways, we assume that electricity is needed from the public electricity grid for the NG liquefaction and LNG is then transported to the end user by road vehicle over an average distance of 100 km. Our modeling assumes that the GTL fuel products are transported like conventional petroleum-based diesel [43] via a mix of railway, waterway and road vehicle transport modes assuming different average distances for each kind of mode.

Table 4. Data of process fuel and transport mode for NG-based fuel.

Pathway	Process fuel mix and percentage	Transport mode [a]
CNG	NG (3%) and electricity (97%)	Road vehicle: 100% (50 km)
LNG	Electricity (100%)	Road vehicle: 100% (100 km)
GTL	NG (100%)	Railway: 50% (900 km); waterway: 15% (1200 km) and road vehicle: 100% (50 km)

Note: [a] Transportation mode: % share (average distance).

Combining the energy intensity and fuel mix data of each transport mode (see Table 5), with the low heat values of the fuels), results in process fuel consumption for 1 MJ of specific CNG, LNG and GTL fuel transported to the end user (see Table 6).

Table 5. Energy consumption intensity and fuel mix for transport.

Mode	Energy consumption intensity/kJ/ton × km	Fuel mix and percentage
Railway	240	Diesel (55%) and electricity (45%)
Waterway	148	Residual oil (100%)
Road	1362	Diesel (68%) and gasoline (32%)

Table 6. Process fuel consumption for NG-based fuel transportation (kJ/MJ through).

Pathway	Diesel	Gasoline	Residual oil	Electricity
CNG	0.96	0.05	0.00	0.00
LNG	1.93	0.09	0.00	0.00
GTL	1.98	0.03	5.95	0.96

3.3. NG-to-Electricity Pathways

Two pathways of NG-to-electricity are selected and their plant net energy efficiency results are listed in Table 7: NG single cycle (NGSC) and NG combined cycle (NGCC). The average loss rate during electricity transmission was 6.97% in 2010 [44] and is predicted to decrease to 6.00% by 2020 [22].

Table 7. Basic parameters of NG-based electricity pathways.

Pathway number	Name	Energy efficiency/%
1	NG single cycle (NGSC)	45
2	NG combined cycle (NGCC)	50

3.4. CCS Capture Rate and Energy Penalty

GTL offers particularly good conditions for CO_2 capture as the gasification process produces a relatively pure stream of CO_2 and the Fisher-Tropsch (FT) conversion necessitates the recovery of undesirable by-products like CO_2 as those inhibit catalyst activity. Thus, for the large quantity of CO_2

that comes from the FT conversion unit only the compression, transport and storage of CO_2 cause additional costs to implement CCS [45].

For GTL and NG-to-electricity (NGCC) pathways for EVs, we determine the maximum capture rate of CCS as: 90% for GTL and 97% for NG power plants [46–48]. According to Jaramillo *et al*. [45], an additional 80–140 kWh of electricity per ton of compressed CO_2 is consumed to fully capture the CO_2 produced in the GTL plant. CCS technology results in an efficiency penalty of about 10% (*e.g.*, efficiency decreases from about 50% to about 40%) for all NG-to-electricity plants under the fully captured CO_2 situations [49].

3.5. Vehicle size and Efficiency in this Study

According to Chinese standards for passenger cars in the 1205~1320 kg-class and less than 750 kg-class respectively, the upper limit for gasoline consumption ranges from 8.6 to 6.2 L/100 km (27.35 and 37.94 mpg) [14]. This study considers the current development trend [50], and assumes the fuel economy of conventional gasoline vehicles will be 6 L/100 km (39.20 mpg) within 10 years for a vehicle weighing about 1000 kg.

Diesel fueled vehicles of the same size can achieve 20% greater energy efficiency due to higher energy (BTU) levels in the fuel itself and associated diesel compression ignition merits [11]. The fuel economy for vehicles using NG-based fuel is assumed to be the same as their substituted fuel during the scenario period.

EV energy efficiency is predicted to be two to three times that of a gasoline vehicle and the potential for much higher efficiencies is possible as battery technologies improve [11,15]. The energy efficiency for EVs, assuming the same size as the 1000-kg-gasoline-car, is 13.2–15.6 kWh/100 km when calculated from the electricity meter usage including losses associated with the charge.

Due to the fact real-world energy consumption rates for vehicles also depend on the driving habits, the fuel efficiency of both conventional vehicle and EV should be lower in real situation than our assumed labeled value.

3.6. Energy Use and GHG Emissions of Vehicle Life Cycle

Like Ou *et al.* [14], we also included the vehicle life cycle impacts for materials production and vehicle manufacturing from Yan [51] (See Table 8) for a medium-sized vehicle in China. The vehicle is assumed with a life of 240,000 km [52], with life cycle energy use and GHG impacts of 0.23 MJ coal, 0.06 MJ petroleum and 27.4 g $CO_{2,e}$ per km, respectively.

Table 8. Life cycle energy use and GHG emissions for the production of a medium-sized passenger car in China [51].

Type	Unit	Amount
Primary energy demand	MJ	69,108
Including, petroleum demand	MJ	14,545
GHG emissions	kg $CO_{2,e}$	6,575

3.7. Energy Use and GHG Emissions of an Electric Battery

The EV pathway has additional impacts due to the material and manufacturing of the different systems (electric motor, batteries, *etc.*). The impacts are also included in this study. We assume that the life cycle energy and GHG emissions listed for 23 kW batteries (See Table 9) in GREET 2.8 for the US situation [52] are in line with the situation in China. The energy use for battery manufacturing is based on scale and power capacity. The numbers for the (30 kW) battery in this study, are obtained by multiplying a conversion factor of 30/23 with the data for 23 kW batteries in GREET 2.8. The study assumes that the battery is replaced once during the vehicle's lifetime of 240,000 km, that's to say the battery has a life time of 120,000 km. Therefore, the resulting impact of life cycle energy use for lithium-ion storage batteries is: 15 kJ of coal, 10 kJ of natural gas and 5 kJ of petroleum per km, respectively. On a life cycle basis, the battery will emit about 7.5 g $CO_{2,e}$ per km.

Table 9. Life cycle energy use and GHG emissions for the battery.

Type	Numbers for 23 kW [a]	Number for 1 kW	Numbers for 30 kW [b]
Fossil fuels/MJ	2778.87	120.82	3624.61
of which: Coal/MJ	1357.26	59.01	1770.34
Natural gas/MJ	943.17	41.01	1230.22
Petroleum/MJ	478.44	20.8	624.06
GHG/kg CO_2-eq	686.03	29.83	894.82

Note: [a] Battery size in peak battery power is 23 kW in Greet 2.8; [b] Battery size in peak battery power is 30 kW in this study.

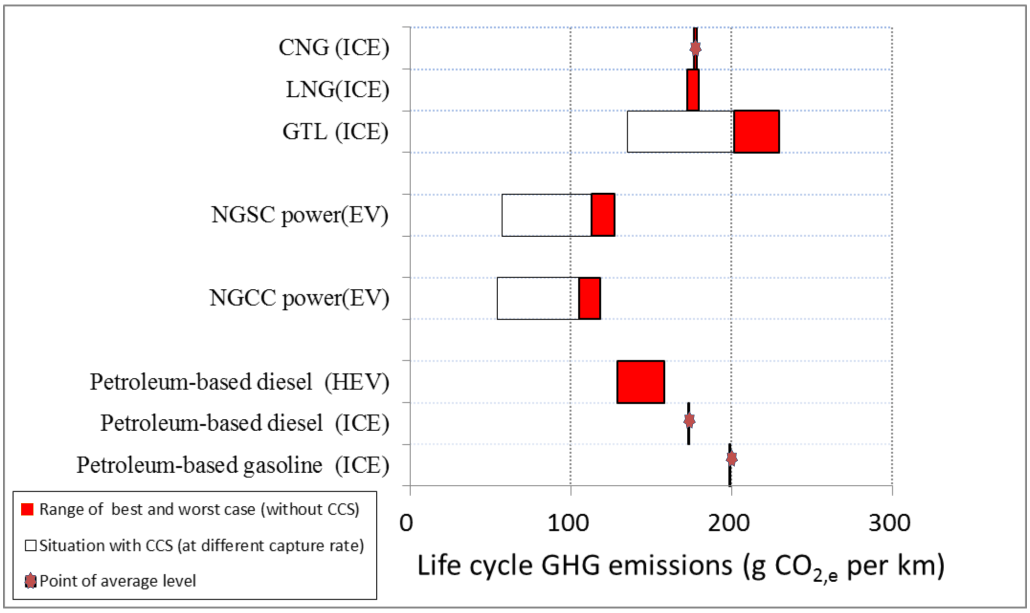
4. Results

4.1. General Description

Figure 2 shows the life cycle GHG emissions for a conventional internal combustion engine (ICE) using petroleum-based and NG based fuel and for an EV using NG-based electricity. The function unit is g $CO_{2,e}$ per km travelled in each vehicle type. This figure shows the range between the high-emissions situation due to low energy efficiency during NG-based fuel production or EV operation stages (represented by the right end of the solid bar: least efficient system configuration) and the low-emissions situation due to high efficiency during NG-based fuel production and EV operation stages (represented by the left end of the solid bar: highest efficient system configuration).

The situations with CCS with different capture rate (range of from 0 to 90%), on the basis of high process energy efficiency, are represented by the boxes on the left of those emission range bars for each NG-based fuel and EV pathway, respectively. For a diesel-based HEV, the bar in the chart show its range of emissions with the efficiency improved from 10% to 30%.

Figure 2. Comparing life cycle GHG emissions of petroleum-based fuels and NG-based fuels by different technologies. (1) Emissions from fuel-cycle and vehicle-cycle are all included; (2) Without CCS, bars depict ranges of highest efficient system configuration (left end point) to least efficient system configuration (right end point); (3) With CCS, bars depict ranges of different rate for CO_2 capture rate.



4.2. Life Cycle GHG Emissions Results without CCS

CNG and LNG pathways both can decrease life cycle GHG emissions by 10% compared to petroleum-based gasoline in a conventional ICE vehicle. For the lower process efficiencies situation, GTL pathway will increase about 15% compared to gasoline while it is comparable to gasoline pathway in the higher process efficiencies situation (CCS still not employed).

In comparison, two pathways for EVs charged by NG-power can potentially decrease life cycle GHG emissions by 43%–47%, in the low emission situations, compared to petroleum-based gasoline in a conventional ICE vehicle. The decreasing rates change to 36%–41% in the high emissions situations.

It is also meaningful to note that using petroleum-based diesel instead of petroleum-based gasoline in ICE vehicles will reduce the use-phase (tailpipe) GHG emissions by about 13% due to higher energy (BTU) values for the fuel and increased efficiency for diesel combustion technologies. Petroleum-based diesel vehicles can also reduce life cycle GHG emissions, when compared to conventional gasoline ICEs, by 20%–35% if hybrid technology is employed.

Therefore, if we change the baseline pathway to petroleum-based diesel HEVs with a 30% improvement from conventional diesel vehicles, then all of the EV pathways in the low emissions situation will decrease life cycle GHG emissions by about 12%–19%. However, in the high emissions situation, EVs will increase life cycle GHG emissions by 1%–9% compared to the diesel HEV baseline. However, all NG-based pathways will increase life cycle GHG emissions dramatically by 38%–78% and 33%–56% in the high and low emissions situations, respectively.

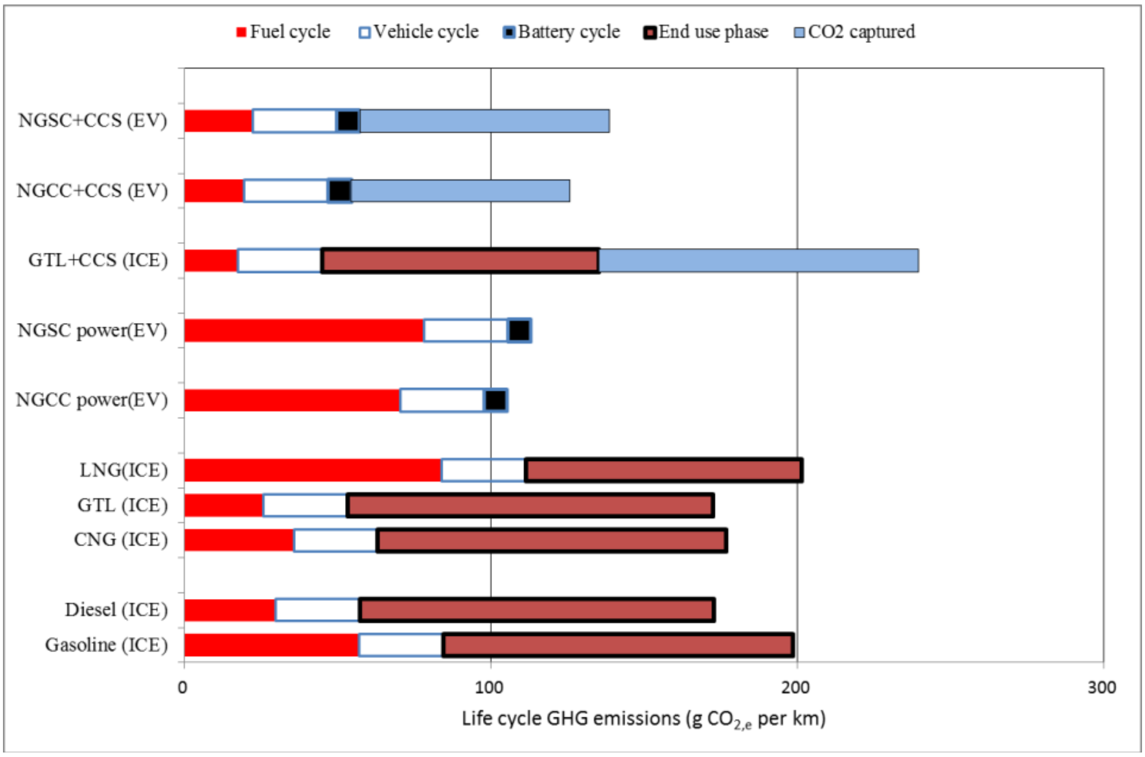
4.3. The Impact of CCS

With CCS technology employed, the GHG emissions situation can achieve better results for GTL fueled vehicles and NG power charged EVs, respectively. The final results using CCS can be even more optimistic for EVs. With maximum rates for CCS capture, NG power charged EVs can decrease life cycle GHG emissions by about 71%–73% and 56%–58% compared to petroleum-based gasoline cars and diesel fueled HEVs, respectively. GTL actually emit life cycle GHG emissions roughly equal to diesel fueled HEVs when used in conventional ICE vehicles. Levels of $CO_{2,e}$ required to be captured ranges from 66 g/MJ fuel and 51–56 g/MJ electricity obtained for vehicle use for GTL pathways and NG-to-electricity pathways.

4.4. The Breakdown of Life Cycle GHG Emissions

As Figure 3 shows, without using CCS, the fuel cycle (including feedstock extraction, transportation, and fuel production and transportation) dominates life cycle GHG emissions (67%–69% for EV pathways). The conventional vehicle cycle (including material production, parts manufacturing and vehicle assemble, disposal and recycling) ranks in second place (about 25%) while the battery life cycle (including battery manufacturing, disposal and recycling) contributes about 7% GHG emissions for NG-power charged EVs. For NG derived liquid fuel vehicle pathways, end use phase emissions contribute 45%–70% of total life cycle GHG emissions. With CCS, the contribution of fuel cycle decreases dramatically for all pathways applied CCS. However, the amount of CO_2 required to be captured is 104 g $CO_{2,e}$ /km for GTL fuel car pathways and 71–81 g $CO_{2,e}$ /km for NG-power charged EV pathways.

Figure 3. Life cycle GHG emissions for NG-based fuel vehicle and EV in the high process efficiency configuration.

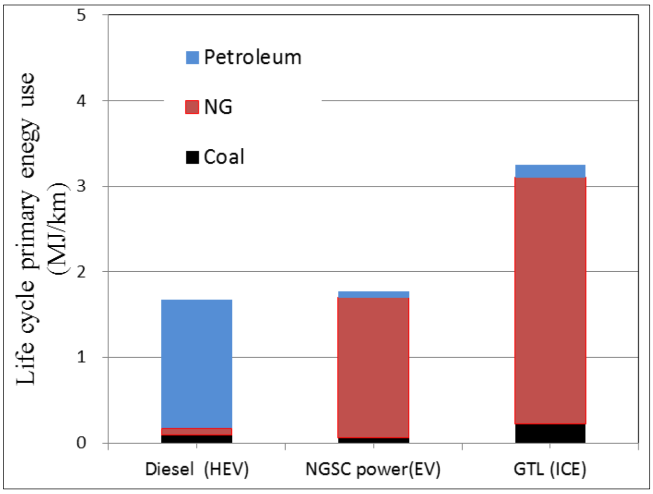


5. Discussions

5.1. Effect of Substituting Petroleum with NG

Through the application of NG-based fuels, the effect of substituting petroleum with NG is obvious, not only for the least efficient system configuration EV pathway (sub-critical NG power and 15.6 kWh/100 km for EV), but also for the least efficient system configuration, the GTL pathway (plant energy efficiency of 54.2% and CCS applied), as shown in Figure 4. For one km travelled, life cycle petroleum use can be decreased by about 90% and 95%, respectively, when compared to a petroleum-based diesel HEV with high efficiency.

Figure 4. Comparing life cycle fossil energy use of three key fuel pathways (HEV in high energy efficiency case while others in low energy efficiency case).



5.2. LNG Supplying Modes and Projection in China

There are three kinds of supply modes for LNG in China: (1) overseas import followed by supply to local cities; (2) liquefaction near gas fields followed by truck transport for final vehicle use; and (3) NG pipeline transport followed by liquefaction, transport, and distribution for vehicle use.

China has signed many long-term LNG sales and purchase agreements (SPAs) and pipe line gas import contracts with Kazakhstan, Turkmenistan, Burma, Indonesia, Malaysia, Iran, Australia and Russia [53]. Qiu and Fang [54] have predicted that China's LNG imports from the Middle East, Australia and Indonesia and pipeline gas imports from Turkmenistan and Russia will reach 40 million tons (about 54 bcm) and 60 bcm respectively by 2020. Based on their forecast, total gas imports will reach 114 bcm by 2020 [6].

5.3. NG Vehicle Development in China

According to the NGV Global statistic, in June of 2012, the ownership of natural gas vehicles in China exceeded 1.1 million, 98.9% of them are CNGV. CNG vehicles have been relatively popular in several regions (*i.e.*, Sichuan, Chongqing, Harbin, Urumqi, and Xi'an) and are primarily used as city buses (replacing diesel buses), taxicabs (replacing gasoline taxis), and governmental automobiles [55].

In 2009, there were 1055 CNG stations across China, 500 more than that at the end of 2007. LNG vehicles have not been widely utilized in China, primarily owing to the lack of LNG sources, the high cost of conversion to LNG, and lack of LNG fueling stations. According to a survey of seven Chinese cities in the end of 2010, 2.8 thousand LNG vehicles were in operation, of which 56% were city buses; a significant proportion of the remainder was accounted for heavy trucks. LNG vehicles are primarily being operated at the demonstration stage and they mainly targeted specific industrial users, and are unable to serve noncommercial LNG vehicles. In the past 2 years, the LNG vehicle market has developed very quickly and the ownership of LNG vehicles in China exceeded 70 thousand, the numbers of LNG refueling stations reached to about 500 as the end of October 2012 [56].

As mentioned in Section 5.2, coastal LNG terminals will gradually be put into production in the near future, so LNG imports will grow exponentially. This trend results in that the LNG sources for LNG vehicle will greatly increase in number with the help of domestic small-scale liquefaction units constructions that are also being built at great speed.

5.4. Energy Use for Battery Manufacture

As researchers noted [57,58], there were many uncertainties in the primary energy use for battery manufacturing, given the direct scaling of energy use based on capacity and assumed battery life time. Though the energy consumption during this stage is likely a small fraction of the whole life cycle, further studies are needed to provide a clearer understanding of material consumption, process energy type and amount for battery manufacturing.

6. Concluding Remarks

(1) EVs look promising as a pathway for reducing GHG emissions when NG is used to power/fuel transportation. Even if NG electricity without CCS is used, EVs reduce life cycle GHG emissions by 36%–47% compared to petroleum-based gasoline in conventional ICE vehicles.

(2) CNG and LNG pathways both can decrease life cycle GHG emissions by 10% compared to petroleum-based gasoline. GTL fuels, on the other hand, will likely increase the GHG emissions associated with transportation fuels when CCS technology is not employed. It actually emit life cycle GHG emissions roughly equal to diesel fueled HEVs with CCS applied in GTL plant. To simultaneously assist with the goals of enhancing oil security while reducing GHG emissions in the passenger transportation sector, EVs (including EVs and PHEVs) are better than GTL fuels.

(3) Almost all NG-based pathways are being developed in China and they are based mainly on the implementation of a portfolio energy strategy that promotes industrial development. However, the GHG emissions will continue to increase. If the goal is to substitute petroleum with NG, then the energy savings dilemma (in particular petroleum saving) and associated increases in GHG emissions, must be carefully comprehended.

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Conflict of Interest

The authors declare no conflict of interest.

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