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Coal-based synthetic natural gas (SNG): A solution to China's energy security and CO_2 reduction?

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HIGHLIGHTS

- ▸ We evaluated life-cycle energy efficiency and CO_2 emissions of coal-derived SNG.
- ▸ We used GREET model and added a coal-based SNG and an end-use modules.
- ▸ The database was constructed with Chinese domestic data.
- ▸ Life-cycle energies and CO_2 emissions of coal-based SNG are 20–100% higher.
- ▸ Coal-based SNG is not a solution to both energy conservation and CO_2 reduction.

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ABSTRACT

Considering natural gas (NG) to be the most promising low-carbon option for the energy industry, large state owned companies in China have established numerous coal-based synthetic natural gas (SNG) projects. The objective of this paper is to use a system approach to evaluate coal-derived SNG in terms of life-cycle energy efficiency and CO_2 emissions. This project examined main applications of the SNG and developed a model that can be used for evaluating energy efficiency and CO_2 emissions of various fuel pathway systems. The model development started with the GREET model, and added the SNG module and an end-use equipment module. The database was constructed with Chinese data. The analyses show when the SNG are used for cooking, power generation, steam production for heating and industry, life-cycle energies are 20–108% higher than all competitive pathways, with a similar rate of increase in life-cycle CO_2 emissions. When a compressed natural gas (CNG) car uses the SNG, life-cycle CO_2 emission will increase by 150–190% compared to the baseline gasoline car and by 140–210% compared to an electric car powered by electricity from coal-fired power plants. The life-cycle CO_2 emission of SNG-powered city bus will be 220–270% higher than that of traditional diesel city bus. The gap between SNG-powered buses and new hybrid diesel buses will be even larger—life-cycle CO_2 emission of the former being around 4 times of that of the latter. It is concluded that the SNG will not accomplish the tasks of both energy conservation and CO_2 reduction.

1. Introduction

China's economy has experienced fast growth for the past three decades. GDP in China grew from 364.5 billion Yuan in 1978 to 47.2 trillion Yuan in 2011. During the same period, China became the largest energy consumption nation in the world. The total energy consumption increased from 16.7 EJ in 1978 to 95.1 EJ in 2010 (National Bureau of Statistics of China (NBS), 2011). Imported energy accounted for 17% of China's total energy consumption in 2010 (National Energy Administration (NEA), 2011). Imported energy, especially petroleum products (65% of its consumption dependent on import), has posed a serious energy security challenge to China. Another big challenge faced by China is CO_2 reduction. China is the largest CO_2 emitter in the world and contributed 23.6% of world total CO_2 emissions from fuel combustion in 2009 (International Energy Agency (IEA), 2011). The Chinese government made a promise at the Climate Change Summit of United Nations in 2009 that China would reduce carbon intensity per GDP in 2020 by 40–45% of 2005 levels. There is an urgent need for China to find solutions to both energy security and CO_2 reduction.

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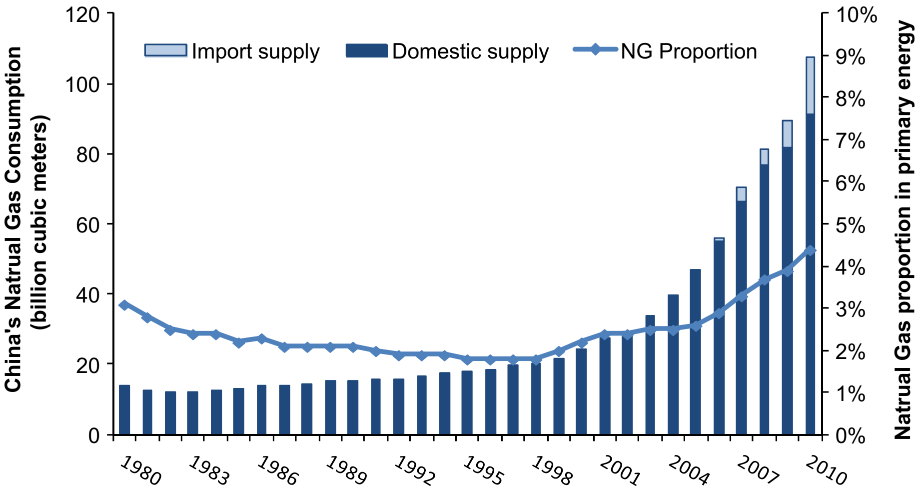

Fig. 1. China's NG consumption and its percentage of primary energy (1980–2010).

NG is currently regarded as the cost effective solution for global warming and energy security. Although NG has been a historically low portion of primary energy consumption in China, its consumption increased significantly in the past ten years, reaching more than 100 billion cubic meters in 2010. However, it was still less than 5% of total primary energy consumption, as shown in Fig. 1. China's 12th five-year-plan (2011–2015) projects NG consumption at 250 billion cubic meters in 2015, accounting for 7.5% of total primary energy consumption. On the supply side, the planned conventional NG output will be 140 billion cubic meters in 2015 (Hu, 2012), while shale gas production is projected to be 6.5 billion cubic meters (National Energy Administration (NEA), 2012). This discrepancy between the projected demand and supply of NG has become a driving force for the recent big wave of SNG projects in China.

SNG can be produced from different feedstocks. For example, due to the carbon-neutral nature of biomass, there are some biomass-based SNG demonstration projects that have been carried out by European institutes, such as Energy Research Center (ECN) in Netherlands, Center for Solar Energy and Hydrogen Research (ZSW) in Germany, and Paul-Scherrer Institute (PSI) in Switzerland and Austria. A commercial project of SNG from forest residues is proposed to construct and commission a 20 MW plant in 2012 and an 80 MW plant by 2016 in Sweden (Kopyscinski et al., 2010).

It seems that co-mingling biomass with coal for gasification is a relative promising option to reduce GHG emissions from coal-based SNG. Although there is no commercial scale operation in the world now, some interesting demonstrations in co-mingling biomass with coal for gasification have been done in US (Raju et al., 2009; Kreutz et al., 2008). High cost of feedstock collection and transportation are two major obstacles for commercial scale biofuel and bio-power production in China, because biomass resources are very scattered in the rural area. There is no plan for commercial plant of biomass-based SNG in China. Instead, some Chinese researchers believe that coal-derived SNG using China's abundant coal reserves will improve energy security, and SNG is a clean-coal technology that will help reduce CO_2 (Liu et al., 2009a; Liu and Xing, 2010).

There are more than 30 coal-based SNG plants (see Table 1) are under construction or planned in China. In Xinjiang Province (in Northwest China) alone, there are plans for twenty coal-based SNG plants, which will have a capacity of 77 billion cubic meters per year. SINOPEC plans to invest 140 billion Yuan (about USD 22 billion) to build 6000 km long pipeline with an annual capacity of transporting 30 billion cubic meters of SNG from Xinjiang to large NG consumers in Southeast China.

Table 1
Ongoing and planned coal-based SNG projects in China.

Investor	Project location	Capacity (billion cubic meters/ year)
DT International Power	Fuxin, Liaoning Province	4.0
DT International Power	Hexigten Banner, Inner Mongolia	4.0
China Huaneng Group	Hulunbeier, Inner Mongolia	4.0
DT Huayin Power	Erdos, Inner Mongolia	3.6
Shenhua Group	Erdos, Inner Mongolia	2.0
Huineng Coal Power	Erdos, Inner Mongolia	1.6
Guodian Corporation	Nilka, Xinjiang Province	10.0
Guanghui New Energy Co.	Yiwu, Xinjiang Province	8.0
China Power Investment Co.	Qapqal, Ili, Xinjiang Province	6.0
China Power Investment Co.	Huocheng, Ili, Xinjiang Province	6.0
Huadian Group	Changji, Xinjiang Province	6.0
Qinghua Group	Yining, Ili, Xinjiang Province	5.5
Beikong New Energy	Qitai, Xinjiang Province	4.0
Henan Coal Chemical Group	Qitai, Xinjiang Province	4.0
LuAn Group	Ili, Xinjiang Province	4.0
China Huaneng Group	Changji, Xinjiang Province	4.0
Xinjiang Longyu Co.	Changji, Xinjiang Province	4.0
China National Coal Group	Changji, Xinjiang Province	4.0
Kailuan Group	Changji, Xinjiang Province	4.0
TBEA Group	Changji, Xinjiang Province	4.0
Yanzhou Mining Group	Changji, Xinjiang Province	4.0
Guanghui New Energy Co.	Altay, Xinjiang Province	4.0
Xuzhou Mining group	Tacheng, Xinjiang Province	4.0
Huahong Mining Co.	Changji, Xinjiang Province	2.0
Xinwen Mining Co.	Ili, Xinjiang Province	2.0
Shengxin Group	Changji, Xinjiang Province	1.6
Tianlong Group	Jimusaer, Xinjiang Province	1.3
UNIS Group	Hami, Xinjiang Province	0.8
Hongsheng New Energy	Zhangye, Gansu Province	4.0
National Ocean Oil Company	Datong, Shanxi Province	4.0
Total		120.4

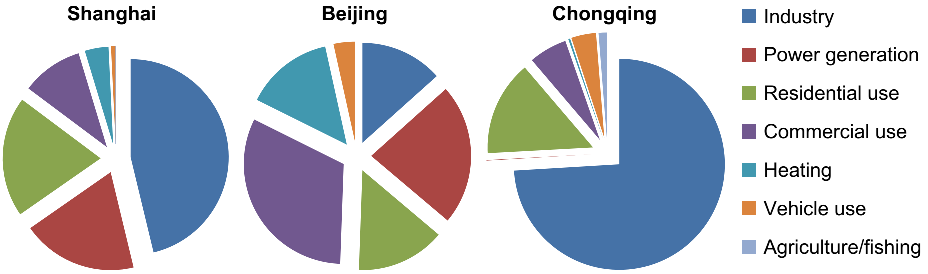

Fig. 2. NG application portfolios for Shanghai, Beijing, and Chongqing in 2010. Note: "Commercial use" includes heating & air conditioning in commercial buildings and cooking in restaurants and hotels. "Heating" only points to gas consumption in concentrated heating system.

Coal can be converted to SNG by thermo-chemical process via gasification and subsequent methanation. After upgrading, SNG can be transported and distributed in existing or newly built pipeline systems. The objective of this project is to evaluate the coal-derived SNG and its applications in a system approach in terms of life-cycle energy efficiency and CO_2 emissions. Findings from this project can provide insights to whether coal-based SNG will be an effective approach for China's path towards energy security and CO_2 reduction.

2. Methodology

The approach used in this project is first to determine main applications of coal-based SNG; second to identify alternatives to SNG for each application; third to define the function unit and scope of the project; and finally to develop a model and database that can be used for evaluating energy efficiency and CO_2 emissions of various fuel pathway systems.

2.1. Main applications of coal-based SNG

Applications of coal-based SNG are similar to those of NG in China. However, NG consumption differs from region to region. NG is delivered to Shanghai by pipelines and as liquefied natural gas (LNG) by ocean tanker. It is mainly used as fuel for industry, cooking, and power generation. Beijing receives its NG through long distance pipelines and NG is additionally used for heating residential and commercial buildings. In areas that have local resources, such as Chongqing, NG is also used as chemical feedstock and transportation fuel (National Energy Administration (NEA), 2011). NG application portfolios for Shanghai, Beijing, and Chongqing are illustrated in Fig. 2. The main applications of coal-based SNG reported in this paper are four categories: cooking, heating, power generation and vehicle use.

2.2. Alternatives to the coal-based SNG applications

SNG can be replaced by carbon free options, such as nuclear power, hydropower, solar power, wind power and biofuels, in some end-use applications. However, China's coal consumption is around 70% of its total energy consumption during 2000–2010, as shown in Table 2. The coal-dominated energy structure has little change in the past decade. One of the key issues of China's energy security and carbon reduction is to use clean-coal technologies efficiently. In this paper, coal is the primary energy source for all fuel pathway analyses except vehicle operation. Each SNG application faces competing alternatives from direct or indirect use of coal. For example, as an alternative to the SNG gas stove application, an electrical-magnet stove can use electricity generated from coal directly. In the vehicle operation application, where a petroleum pathway is used as a reference, imported LNG can be a tough completive option to the SNG. The SNG pathways and their competitive alternatives are shown in Table 3.

Table 2
Percentage of China's total energy consumption (%).

Year	Coal	Oil	NG	Hydro, nuclear, wind, biomass, solar
2000	69.2	22.2	2.2	6.4
2010	68.0	19.0	4.4	8.6

2.3. Scope and function units

Operational definitions of the scope of life-cycle assessments reported in the current study are illustrated in Fig. 3. For life-cycle analysis of cooking, heating, and power generation pathways, the function unit is defined as an output of 1 MJ low heat value (LHV) energy. The total energy use and CO_2 emissions of all pathways are compared on a basis of output of 1 MJ energy. Total life-cycle energy use is a summation of upstream and downstream energy consumption, including the 1 MJ output itself. For vehicle operation pathways, the function unit is defined as 1 km traveled by a five-seat compact car. Total life-cycle energy use is a summation of energy consumption during fuel process and fuel consumption per km traveled by the car. The total energy use and CO_2 emissions of all vehicle operation pathways are compared on the basis of km traveled by the car.

Two major assumptions were used in the study. One is that the scope of analyses was limited to energy consumption and CO_2 emissions in the fuel cycle and did not cover those occurring during equipment manufacturing and infrastructure construction. The other is that all greenhouse gases (for example, methane) were converted to CO_2. Greenhouse gas (GHG) emissions are expressed in terms of grams CO_2-equivalent (gCO_2-eq.). The "equivalence" is based on the conventional global warming potentials (GWPs) of respective individual GHGs for a time span of 100 years. Because radiative forcings are time dependent, so are the GWPs. The GWP value provided by the Intergovernmental Panel on Climate Change (IPCC, 2007) for the methane (CH4) is 25[1].

2.4. Model and database

This project used the GREET (greenhouse gases, regulated emissions, and energy use in transportation) model (Wang, 2005) as a reference, and then added a coal-based SNG module and an end-use equipment module. As our previous study on China's fuel-cycle analysis (Shen, 2007; Shen et al., 2012), the database was

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[1] More recently, by incorporating gas–aerosol interactions, some researchers have indicated that the methane GWP ought to be revised upward to about 33 (Shindell et al., 2009). This revision is not considered here.

Table 3
Coal-based SNG applications and competitive alternatives.

	Heating	Cooking	Power generation	Vehicle use
SNG application	SNG-fired boiler	Gas stove	NGCC with SNG	NGV using SNG
Competitive alternative	Coal-fired boiler	Electric-magnet stove	Coal-fired plant	Gasoline vehicle Electric vehicle NGV using domestic NG/LNG

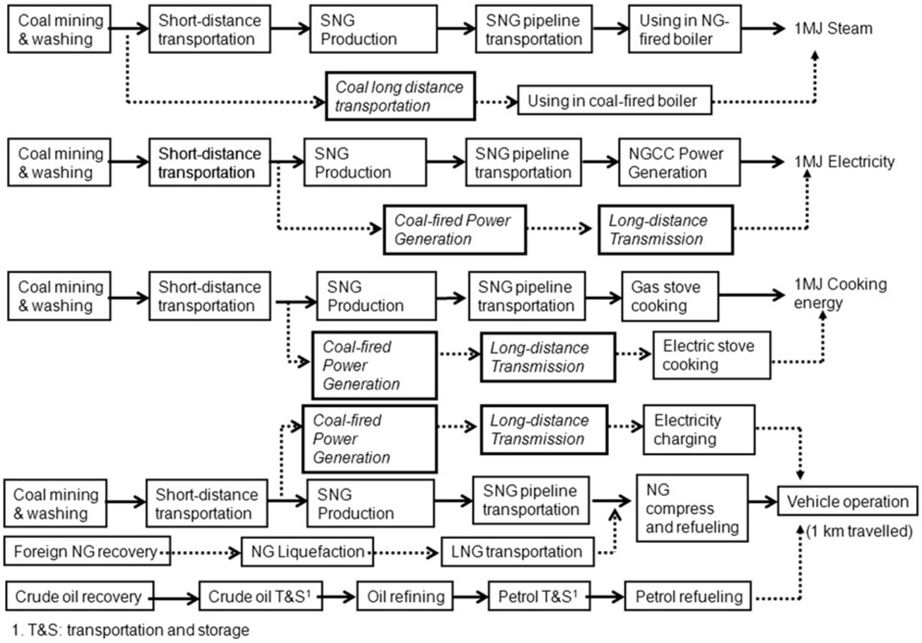

Fig. 3. Scope of life-cycle analysis of coal-based SNG and alternative pathways.

constructed fully with Chinese domestic data. Data were collected through literature search, field survey, interviews and private communication.

3. Model development

The model consists of five modules: (1) coal mining, washing, and transportation; (2) SNG production and pipeline transportation; (3) power generation; (4) petroleum and LNG; and (5) end-use equipment. This model is used for life-cycle analyses of coal-based SNG applications and its competitive alternatives. The data for each module are described below.

3.1. Coal mining, washing and transportation

China consumes more than 3 billion tons of coal each year. Subsurface mining dominates the industry, accounting for 95% of coal mining production in China. Mining 1 t of coal, consumes 34 kWh electricity and 27 kg raw coal (Chinese Coal Research Institute (CCRI), 2006); and emits 7–10 cubic meters of methane (Zheng, 2002; Ma et al., 1999) and 6 cubic meters CO_2 (Chinese Coal Research Institute (CCRI), 2006). About 25% of the coal produced in China was cleaned and sorted in 2010 (National Energy Administration (NEA), 2011). For each ton of coal cleaned and sorted, 3 kWh electricity was consumed. There is about 10% coal gangue eliminated during the cleaning and sorting process that has a total energy efficiency of 95% (Chinese Coal Research Institute (CCRI), 2006). All coal-based SNG plants are located near coal mines. It is assumed that coal is transported by diesel truck no more than 50 km. The fuel consumption of back-haul of empty trucks is considered in the analysis. For coal-fired power plants and other coal-fired boilers, coal transport is comprised of 45% railway, 40% highway and 15% waterway, as shown in Table 4. The average transport distance is 640 km for railway, 1500 km for waterway (coal for power generation is often transported by barge from ports in North China to the 7 southeast provinces), and 500 km for highway.

3.2. Coal-based SNG production and pipeline transportation

Coal-based SNG production requires several steps. The first step is the pro-processed coal is gasified in presence of catalysts. After the producer gas cleaning and conditioning, the carbon oxides in it are converted to methane in methanation, a heterogeneously catalysed hydrogenation process. To reach quality requirements of the gas pipeline system, the impurities like water and carbon dioxide have to be removed in SNG upgrading step, at the end of the process chain.

Coal gasification technologies can be divided into three types: fixed bed, fluidized bed, and entrained flow gasification. The representatives of fixed bed process are Lurgi and its improved system—BGL. The methane content of producer gas from Lurgi and BGL is relative high—an advantage for subsequent methanation step. The only existing commercial coal-based SNG plant outside China—Great Plains Synfuels Plant in North Dakota consists 14 Lurgi Mark IV fixed-bed gasifiers (Kopyscinski et al., 2010). Some fluidized bed system (HTW and Shaanxi U-gas) are still used in China, although the carbon conversion efficiency and unit scale are not as good as expected. From 1978, more than 80 entrained

Table 4
Key parameters of coal long-distance transportation.

	Waterway	Railway		Truck
Mode share (%)	15	45		40
Distance (km)	1500	640		500
Fuel type	Fuel oil	Diesel	Electricity	Diesel
Energy intensity (kJ/t km)	257	203	78	1480

flow gasifiers from Texaco and Shell have been introduced to China. Several domestic gasification technologies have been developed and commissioned from 1990. The opposed multi-burner (OMB) gasifier proved to reach higher conversion efficiency and lower coal and oxygen consumption rate than Texaco process (Li and Shen, 2011). Most of China's commercial SNG plants under construction choose Lurgi or OMB gasifiers. The coal category adaptability of Lurgi is better than OMB. The energy efficiency of the entire SNG process of these technologies is in a range from 46 to 55% (Liu et al., 2009a; Liu and Xing, 2010).

Two representative cases of pipeline transport of SNG were assessed in this study: the first one was from Hexigten to Beijing at a distance of 500 km; and the second one was from Xinjiang to the east coast at a distance of 4000 km. The energy consumption for NG pipeline transport is about 1.1 MJ/(1000 m^3 km) (Xie, et al., 2006), which is 3–9 times higher than energy used in coal transportation by railway. From energy saving perspective, long-distance pipeline would not be a good choice for transportation of SNG programs.

3.3. *Power generation*

Coal-fired power plants accounted for 77% of China's total power generation in 2010, and only 2% were power plants using NG and LNG. Coal-fired power plants consumed almost half of coal produced in China, compared to 17% NG and LNG used for power generation (National Energy Administration (NEA), 2011). To reduce air pollution in big cities such as Beijing, coal-fired units are replaced with gas generation units. Newly built coal-fired units are in remote locations. Electricity is transmitted long distances to urban customers. Data released by the State Electricity Regulatory Commission (SERC) indicates that in 2010 there was a 6.5% loss of electricity during the long distance transmission, which is comparable to US rates for 2007 (State Electricity Regulatory Commission (SERC), 2010).

The mainstream coal-fired power generation units in China are 300–600 MW subcritical and supercritical units, accounted for 68% of total coal-fired power generation units in 2010. Ultra-supercritical (USC) system is less than 5% (CEC, 2012). Statistical data, literature reviews and field surveys indicated that from 2008 to 2010, power supply efficiency for subcritical, supercritical, and USC coal-fired power generator units were 34–40%, 38–41%, and 39–43%, respectively. We use 36% and 42% as the median value for subcritical and ultra-supercritical sets.

Typical gas-fired power generation technologies deployed in China are 180 MW natural gas combined cycle (NGCC) and fast growing 350 MW NGCC in the past five years. Among 119 NG-fired power plants surveyed, 64 units were 350 MW NGCC and 46 units were 180 MW NGCC. These surveyed NG-fired power plants accounted for 98% of gas-fired power generation capacity. Their theoretical power supply efficiencies could reach 50% and 55%, respectively. However, statistical data shows that the capacity factor (CF) of most of Chinese gas-fired power generation units was only in a range of 30% to 50% in recent years (State Electricity Regulatory Commission (SERC), 2010). Ye (2011) proved that gas-fired power generation units had a 20% increase in heat loss when they operated at 40% load. Zhou and Zhai (2009) showed that power supply efficiency would be reduced from 51% to 42% when CF decreased from 100% to 60%. Power supply efficiency of 50% is used for calculation of SNG power generation although the real efficiency may lower than it.

3.4. *LNG*

The SNG can be used as fuel for a compressed NG vehicle (CNGV) and compared a baseline gasoline car. For a CNGV, the SNG is a substitute of conventional NG. LNG is another competitive alternative. Australia, China's largest LNG supplier, provided more than 40% oversea LNG to China in 2010 (British Petroleum (BP), 2012). An average distance of 6000 km is used in this study for Australian LNG transport by ocean tanker to China. The LNG is vaporized in the terminals, transported via pipelines and compressed in refueling stations for CNGV. An average distance for LNG transport from receiving terminals to urban fueling stations is assumed as 100 km. Energy efficiency for LNG process is generally 85–93% (Sinopec, 2008). Compression efficiency in refueling station by electric compressor is about 98% (Shen, 2007).

3.5. *End-use equipment*

There are two types of boilers used for generating heating or industry steam: coal-fired boilers and gas-fired boilers. Authoritative monitor data collected in difference provinces by State Administration for Quality Supervision and Inspection and Quarantine (AQSIQ) shows that more than 95% industry boilers operated in China are those with unit capacity less than 20 t/h and their CF is usually between 50% and 70%. The efficiency of coal-fired boilers was between 55% and 75% with an average of 69%; efficiency of gas-fired boilers was between 80% and 85% with an average of 83% (Wang, 2005b). Carbon oxidation rate is 90% for coal-fired industry boilers and 99.5% for gas-fired industry boilers (C4S Working Group, 2000).

In cooking equipment, electric-magnet stove with efficiency (energy efficiency in cooking process, not the transformation efficiency of the equipment itself) of 77–80% is the major competitive alternative to gas stove with an efficiency between 43% and 52% (Li and Jiang, 2006; Liu et al., 2009b).

For CNGV application, the compressed gas fuel can come from conventional NG, coal-based SNG, or imported LNG. In China, CNG is used to fuel passenger cars (including taxi and private cars) and city buses. To analyze CNG-powered passenger car, an MY2010 gasoline car is used as a baseline. It has a gross vehicle weight (GVW) about 1300 kg, port-injection spark-ignition (PISI) engine displacement 1.8 l coupled with a 5-speed standard automatic transmission, and fuel consumption of 8 l/100 km in NEDC (New European Drive Cycle) test. The baseline car uses RON 93 gasoline and meets the Euro-IV emission standard. It is assumed that dedicated CNG car has the same efficiency as the baseline (for a retrofitted car to use bi-fuels, the energy efficiency will be a little lower). Battery electric vehicle (BEV) using electricity from coal-fired power plants can be another competitive alternative to the CNG car powered by SNG. Energy consumption for electric car is 20 kWh/100 km used in this study, although it could be around 15 kWh/100 km for electric cars made by some international OEMs. The fast charging loss is 10% at the BEV charging stations.

Most city buses operated in China use diesel as fuel. CNG bus, LNG bus[2] and diesel hybrid bus have been introduced during recent years. In China's large cities, electric buses are not very successful in several demo projects because of their much lower service-availability rate caused by limited travel range and long

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[2] LNG can be directly used to power heavy duty vehicles.

charging time. In this study, we choose a diesel city bus with a fuel consumption rate of 30 l/100 km in "China test cycle" (Zhang, 2007) as baseline. According to Wu (2012), fuel efficiency of diesel hybrid bus is 20–25% higher than baseline while that of CNG bus and LNG bus will be 20% lower than baseline in their field survey.

4. Results and discussion

Life-cycle analyses for the SNG used in cooking, power generation, steam production for heating and industry use, and vehicle operation were carried out against their competitive alternatives. The outputs of energy use and CO_2 emissions are summarized below for all pathways, including their feedstock extraction, fuel production, fuel transport, end use, and entire life-cycle.

4.1. Pathways for cooking

Results of four cooking pathways are summarized in Fig. 4. Although coal-based SNG is more efficient in fuel production stage, overall energy efficiency is lower than electric-magnet pathways, because electric-magnet stoves have higher efficiencies than gas stoves in cooking process. When coal-based SNG is transport at a distance of 500 km, it takes 4.3 MJ of life-cycle energy to generate 1 MJ effective cooking energy. The overall energy efficiency is 23%. When the SNG is transported at a distance of 4000 km, the life-cycle energy of coal-based SNG for cooking is increased to 4.9 MJ and the efficiency is 20%. When electric-magnet stoves used as competitive alternatives, the life-cycle energies are 4.1 MJ for power from subcritical unit and 3.5 MJ for USC unit. The USC pathway has the highest energy efficiency of 29%, of which total energy use can be 19% and 30% less than the two SNG pathways.

Similarly, coal-based SNG emits less CO_2 in upstream than electric-magnet pathways, but has a higher life-cycle CO_2 emission. When transported at a distance of 500 km and 4000 km, life-cycle CO_2 emissions of the SNG pathways are 458 $gCO_2eq.$ and 525 $gCO_2eq.$ Life-cycle CO_2 emissions for electric-magnet stove pathways are 431 $gCO_2eq.$ for using subcritical unit and 369 $gCO_2eq.$ for employing USC unit.

4.2. Pathways for power generation

Results of four power generation pathways are summarized in Fig. 5. When the SNG is transported at a distance of 500 km and 4000 km, it takes 4.3 MJ and 4.9 MJ of life-cycle energy to generate 1 MJ electricity for grid in urban residence area. When coal-fired power generation used as competitive alternatives, the life-cycle energies are 3.2 MJ for subcritical unit and 2.7 MJ for USC unit. Corresponding life-cycle CO_2 emissions for the SNG pathways are 458 $gCO_2eq.$ and 525 $gCO_2eq.$, which suggests 36%

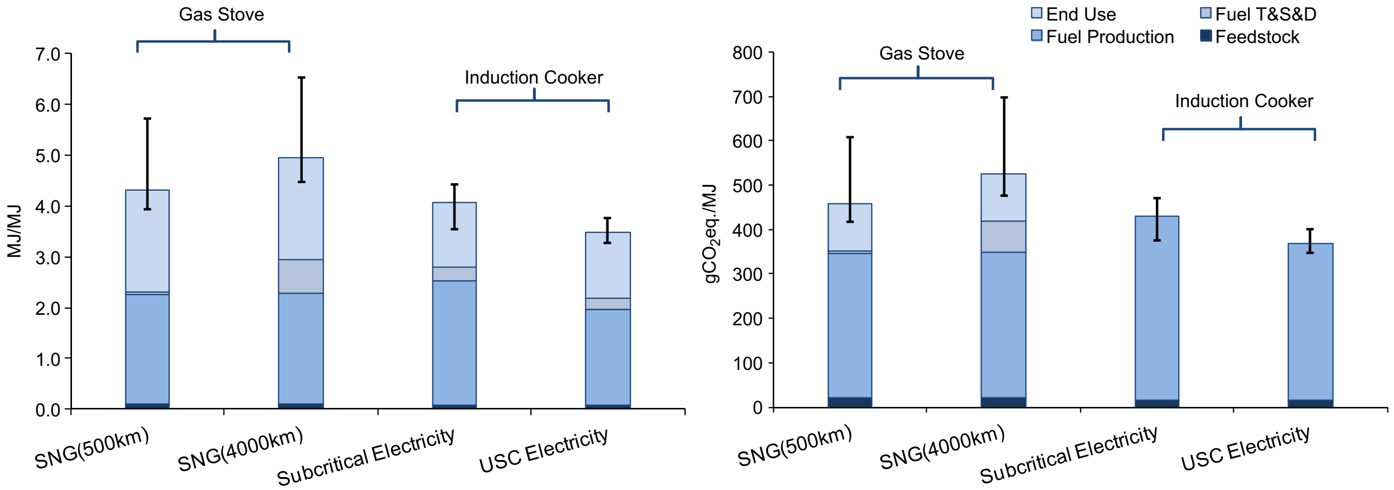

Fig. 4. Life-cycle energy use and CO_2 emissions of SNG and competitive pathways in cooking. Note: Fuel T&S&D shows energy use and GHG emissions of fuel transportation, storage and distribution, including long distance transmission of electricity.

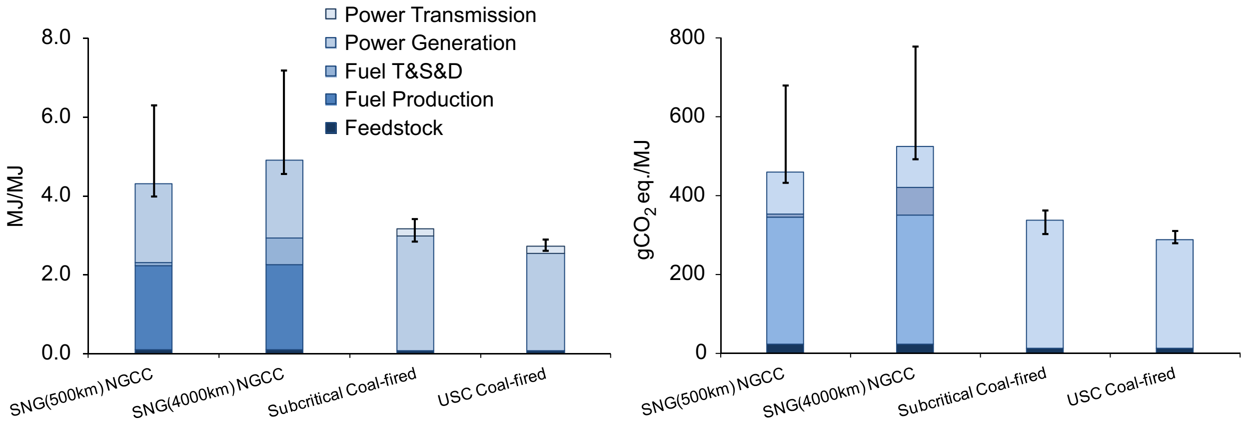

Fig. 5. Life-cycle energy use and CO_2 emissions of SNG-fired power generation and competitive pathways.

and 56% higher than subcritical pathway and 59% and 82% higher than USC pathway.

4.3. Pathways for steam production for heating and industry use

Results of three pathways for steam production are summarized in Fig. 6. As can be seen, although efficiency of gas boilers is much higher than coal-fired boilers, life-cycle energy efficiency of boilers using coal-based SNG is lower than coal-fired boilers due to high energy consumption during SNG production process. It takes 1.6 MJ of life-cycle energy for coal-fired boiler pathway to produce 1 MJ of steam or hot water. The life-cycle energies for two coal-based SNG cases are 2.6 MJ and 3.0 MJ, which are 68% and 92% higher than the coal-fired boiler pathway. Life-cycle CO_2 emission is 152 $gCO_2eq.$ for coal-fired boiler pathway, while the life-cycle CO_2 emissions for the two SNG cases are 276 $gCO_2eq.$ and 316 $gCO_2eq.$, respectively. The overall efficiency of two SNG cases are only 38% and 34% while that of coal direct use pathway can reach 65%.

4.4. Pathways for vehicle operations

Results of seven pathways of passenger car operations are summarized in Fig. 7. Wheel-to-Well (WTW) study of the baseline gasoline pathway shows that life-cycle energy and CO_2 emissions are 3.3 MJ/km and 249 $gCO_2eq.$, respectively. For CNG car using inland NG transported at a distance of 4000 km, WTW energy consumption is 3.4 MJ/km but WTW CO_2 emissions will be reduced 5%. When SNG transported at a distance of 500 km and 4000 km, WTW energy consumption of CNG car increased to 5.8 MJ/km and 6.6 MJ/km, which are 74% and 99% higher than the gasoline car. CO_2 emissions of the two SNG pathways are increased to 633 $gCO_2eq.$ and 721 $gCO_2eq.$, which are 154% and 189% higher than the gasoline car. CNG car using LNG is more competitive. The life-cycle energy and CO_2 emission of LNG pathway are 2% and 14% less than the baseline gasoline car.

Compared to CNG car using coal-based SNG, electric car using coal-fired electricity is more attractive. Energy consumption and CO_2 emission of electric car using electricity coming from subcritical generation unit are 2.51 MJ/km and 266 $gCO_2eq.$, respectively. WTW energy use of electric car is 25% less than the baseline gasoline car and CO_2 emission is 7% higher than the baseline gasoline car. Compared to CNG car using SNG transported at a distance of 500 km and 4000 km, CO_2 emissions of electric car are reduced 58% and 63%. If USC generation unit is deployed, WTW energy and CO_2 emission of electric car are further reduced to 2.17 MJ/km and 231 $gCO_2eq.$, which are 35% and 8% less than the baseline gasoline car. WTW CO_2 emission of electric car using USC electricity is 64% and 78% less than the two SNG pathways.

Results of six pathways of city bus are summarized in Fig. 8. Life-cycle energy and CO_2 emission of traditional diesel city bus are 13.4 MJ/km and 1008 $gCO_2eq.$, respectively. WTW CO_2

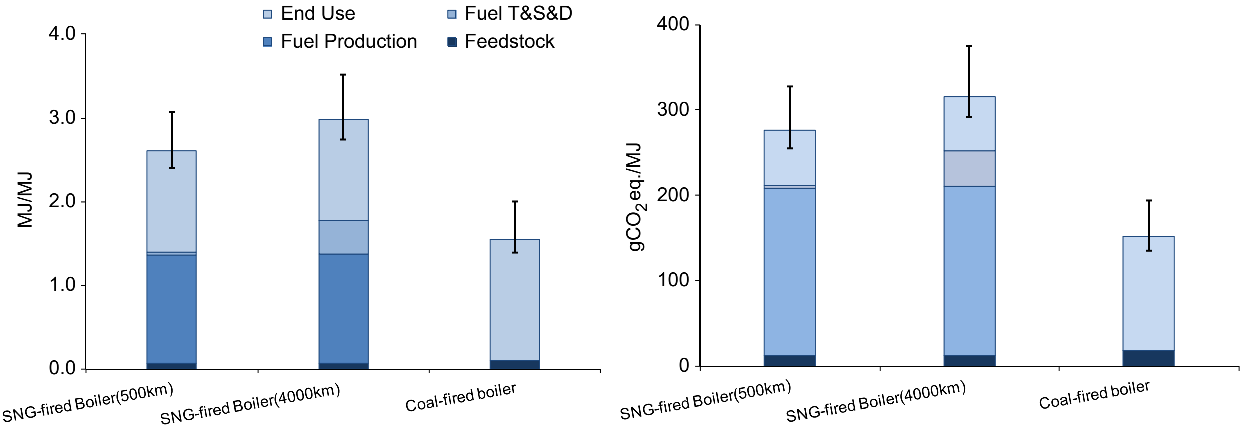

Fig. 6. Life-cycle energy use and CO_2 emissions of SNG heating and competitive pathways.

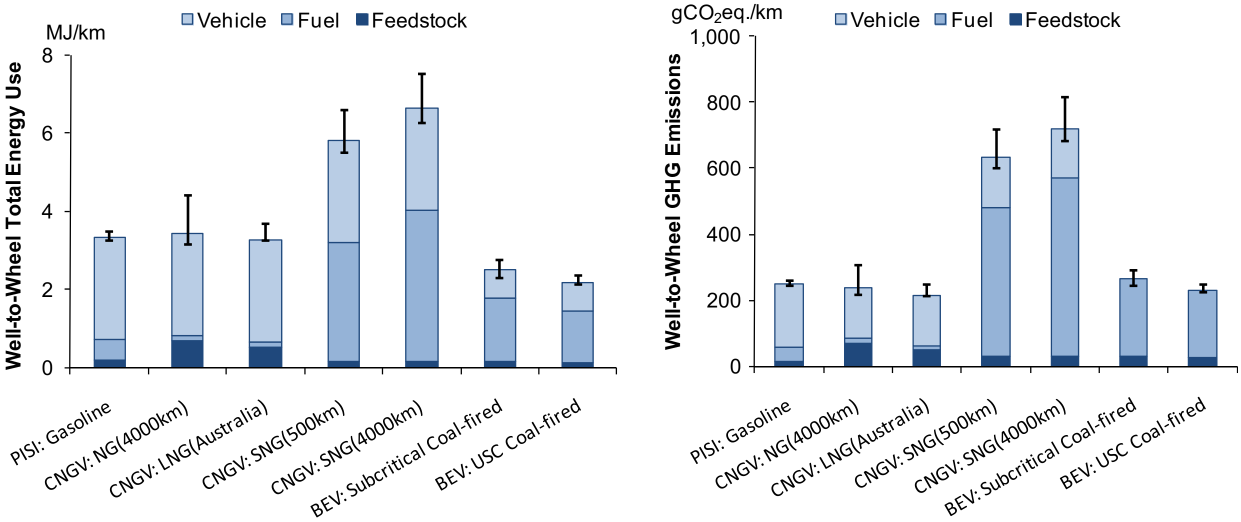

Fig. 7. Well-to-wheel energy use and CO_2 emissions of SNG-powered CNG car and competitive pathways.

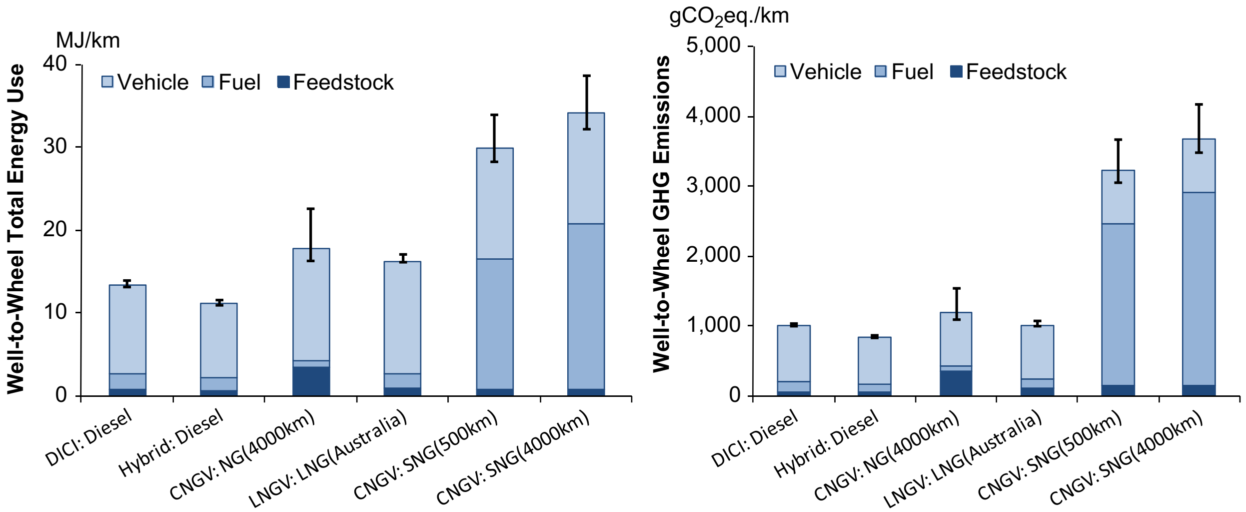

Fig. 8. Well-to-wheel energy use and CO_2 emissions of SNG-powered CNG city bus and competitive pathways.

emission of LNG bus using imported NG will be equivalent to diesel bus. When SNG transported at a distance of 500 km and 4000 km, WTW CO_2 emissions of SNG-powered CNG bus will increase to 3235 $gCO_2eq.$ and 3685 $gCO_2eq.$, which are 221% and 265% higher than the diesel buses. New introduced hybrid diesel bus, on the contrary, is much more competitive on global warming impact, with a 20% carbon reduction than traditional diesel pathway.

5. Conclusions and implications

In order to address energy security and achieve the promised 2020 target of reducing by 40–45% the carbon intensity per GDP, the Chinese government is actively promoting a transition towards a low carbon energy structure. Because NG is considered to be the most promising low-carbon option for the energy industry, large state owned companies have established numerous coal-based SNG projects. The life-cycle analyses in this study indicated that coal-based SNG has poor life-cycle energy efficiencies and high CO_2 emissions, which suggests that the SNG are not right options for both energy conservation and CO_2 reduction in China.

The analysis shows when coal-based SNG is used for cooking, power generation, and steam production, life-cycle energies are 20–108% higher than all competitive pathways, with a similar rate of increase in life-cycle CO_2 emissions. The CNG car using domestic NG or imported LNG can reduce CO_2 emissions by 5–14% compared to the conventional gasoline car. If CNG car uses SNG, the life-cycle CO_2 emission will increase by 180–220% compared to the gasoline car and by 160–240% compared to the BEV pathway.

The coal-based SNG pathways will accelerate depletion of coal resources due to its lower life-cycle energy efficiency. Using Beijing as an example, the NG consumption percentages of residential use, power generation and steam production (for heating, commercial use and industry use) are 25%, 15%, and 60%, respectively. If using the competitive and alternative pathways to substitute SNG (500 km pipeline) pathway, the energy consumption could be reduced by 37%. China government has approved a SNG project to supply Beijing with a capacity of 10 billion cubic meters per year, which will consume about 30 million tons of coal per year. Using the competitive and alternative pathways, 11.2 million tons of coal will be conserved each year, equivalent to annual coal consumption of six 1 GW level power plants and 42% of Beijing's coal demand in 2010.

There will be serious economic consequences from coal-based SNG projects. The regions that are developing SNG projects also have natural gas resources. The NG price at the gate of natural gas field is between RMB 0.79 Yuan and 1.21 Yuan per cubic meter now. Reasonable prices at SNG factories should be close to the NG price. To make the SNG plant cost effective, the cost of coal needs to be controlled below 40% of the SNG price, which means acceptable feedstock coal price should not beyond RMB 160 Yuan/t. This "acceptable price" is only 25% of the coal price at the China's biggest coal distribution center—Qinhuangdao Harbor and two third of the mine-head price in Erdos, which will lead to a great risk of economic viability of all SNG projects.

Shale gas is estimated more than 36 trillion cubic meters in China, which is more than ten times than proved conventional NG reserves (Energy Information Administration (EIA), 2011). It is important for China to explore shale gas instead of coal-based SNG as a core of its low-carbon energy structure. China's coal resource is only relative rich—with an *R*/*P* (reserve vs. production) ratio 33 (British Petroleum (BP), 2012), only 1/3 of world average level. China has become a net coal importer from year 2009 and China's coal import has reach 182 Mt in 2011 (National Bureau of Statistics of China (NBS), 2012). The SNG projects are not qualified as a solution to energy security and global warming mitigation.

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