Life cycle energy use and GHG emission assessment of coal-based SNG and power cogeneration technology

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Abstract:

Life cycle energy use and GHG emissions are assessed for coal-based synthetic natural gas (SNG) and power cogeneration/polygenereation (PG) technology and its competitive alternatives. Four main SNG applications are considered, including electricity generation, steam production, SNG vehicle and battery electric vehicle (BEV). Analyses show that if SNG is produced from a single product plant, the lower limits of its life cycle energy use and GHG emissions can be comparable to the average levels of coal-power and coal-BEV pathways, but are still higher than supercritical and ultra supercritical (USC) coal-power and coal-BEV pathways. If SNG is coproduced from a PG plant, when it is used for power generation, steam production, and driving BEV car, the life cycle energy uses for PG based pathways are typically lower than supercritical coal-power pathways, but are still 1.6-2.4% higher than USC coal-power pathways, and the average life cycle GHG emissions are lower than those of all coal-power pathways including USC units. If SNG is used to drive vehicle car, the life cycle energy use and GHG emissions of PG-SNGV-power pathway are both much higher than all combined coal-BEV and coal-power pathways, due to much higher energy consumption in a SNG driven car than in a BEV car. The coal-based SNG and power cogeneration technology shows comparable or better energy and environmental performances when compared to other coal-based alternatives, and is a good option to implement China's clean coal technologies.

Keywords:

Life cycle, Energy use, GHG emissions, SNG, Cogeneration

1. Introduction

China's total energy consumption amounted to 3.75 billion tons of coal equivalence in 2013 and ranked first in the world [1]. The energy consumption in China is still dominated by coal, although its share in total energy consumption has been decreasing in recent years (70.4% in 2009 and 66.0% in 2013) [2]. At the same time, the annual oil and gas consumptions in China are climbing at an average rate of 5.0% and 16.4% in the past five years, respectively [2]. With the increasing demand of oil and natural gas (NG), the oil dependency in China reached around 70% in 2012, and the gas dependency grew from 5.6% in 2008 to around 29% in 2012 (China imported around 42.1 billion cubic meters natural gas in 2012) [2]. High reliance on imported energy, especially the natural gas, has posed a serious energy security challenge to China. Another great challenge faced by China is CO_2 reduction. Based on a statistic by International Energy Agency (IEA), China emitted 8.2 GtonCO_2 in 2012 (26% share of world emissions) and became the largest CO_2 emitter [3]. Most of China's CO_2 emissions came from coal combustion. Hence, aiming at the two goals of enforcing energy security and reducing global warming gases, how to utilize coal to produce clean energy is an important issue for China.

Under such background, numerous synthetic natural gas or substitute natural gas production projects from coal have been proposed and established with additional driving forces of increasing NG price in China [4, 5]. Until the end of 2014, the total capacity of planned coal to SNG summed up to around 15-18 billion cubic meters [6]. As one of the prevailing coal to alternative fuel pathways, coal to SNG in a single product plant receives controversy due to its potential high life cycle energy use and CO_2 emissions compared to traditional coal to power or conventional natural gas pathways [4, 7]. However, if SNG is produced in a cogeneration (PG) plant instead of a single product plant, it was reported that the energy efficiency of the plant can be significantly improved, which may result in a much lower life cycle GHG emissions and energy uses [8-11]. The coal-based cogeneration technology to produce both alternative fuels, such as liquid fuel and SNG, and electricity was recognized as a good solution in order to realize the decarbonization and efficient use of coal in China [8-11].

In this paper, based on our previous studies on techno-economic performance evaluations of SNG and power cogeneration technology [8-11], the life cycle energy use and GHG emissions of this clean coal option will be assessed compared to its competitive alternative pathways. A model that can be used to evaluate the life cycle efficiency and GHG emissions of coal-based SNG and power cogeneration technology will be developed based on a Chinese domestic database. Findings from this paper can provide insights to whether coal-based SNG and power cogeneration will be an effective approach towards energy security, clean coal, and CO_2 reduction in China.

2. Methodology

In this section, life cycle assessment is quantified, and the database for each technology considered in different pathways is constructed.

2.1 - Coal-based SNG and power cogeneration technology

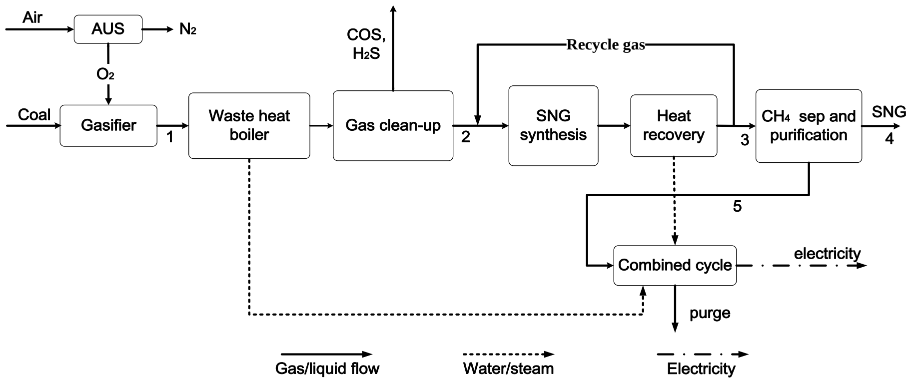


Fig.1. *Coal-based SNG and power cogeneration technology (1-raw syngas; 2-fresh syngas; 3-raw SNG; 4-final SNG product; 5-off gas) [10]*

The coal-based SNG and power cogeneration technology is shown in Figure 1 [10]. Coal is gasified at the presence of oxygen from air separation unit (ASU) to produce raw syngas. Then the raw syngas is sent to gas clean-up unit to remove COS and H_2S after heat recovery in a waste heat boiler (WHB). The clean and fresh syngas is used to synthesize SNG. Afterwards, the unreacted gas leaving the synthesis reactor was partially recycled back to control the product rate of final SNG product. Another flow split of unreacted gas is sent to CH_4 purification unit to generate SNG with high CH_4 purity over 90%. The off gas from CH_4 purification unit containing unreacted CO, CO_2 & H_2 is sent to combined cycle unit for power generation. The high-temperature steams recovered from WHB and SNG synthesis unit are used to generate power in combined cycle unit. By such system integrations, SNG and power can be coproduced efficiently [10].

2.2 - Article 2 SNG utilization pathways and the competitive alternatives

SNG applications in China are similar to natural gas (NG) and differ from region to region in China. In big cities such as Beijing, new construction of coal-fired power plants is not permitted and NG is used to generate electricity in natural gas combined cycle (NGCC) power plants in order to reduce air pollutions [4]. Besides, NG is used for cooking, heating and vehicle fuel [4, 12]. In some areas that have local resources, e.g. Chongqing, NG is also used as chemical feed-stock. According to the main applications of SNG, four main pathways of coal-based SNG and power cogeneration are considered in this paper: (1) PG-power pathway. SNG produced from PG plant is transported via pipeline to urban areas and then fired in a NGCC power plant to generate electricity. The electricity cogenerated in PG plant is transmitted long distance to urban areas. Two main competitive coal alternative pathways are considered for PG-power pathway. The first option is to transmit electricity from coal-fired power plants in remote locations to urban consumers (coal-power pathway). And the second alternative is to transport SNG produced in a single product plant (only produces SNG) to generate electricity in a NGCC power plant located in urban areas (single SNG-power pathway). (2) PG-steam-power pathway. In this pathway, SNG is used to produce steam and power from the PG plant is the co-product. The main alternative for PG-steam-power pathway is the combination of coal-power and coal-steam, in which coal is transported long distance to produce steam in a boiler located in urban areas (coal-steam pathway). (3) PG-SNGV-power pathway. SNG is used as vehicle fuel, and electricity from PG plant is sent to the end users as another product in this pathway. The combined coal-power and coal-BEV pathways are considered as alternatives. In the coal-BEV pathway, electricity from the coal-power pathway is used to drive battery electric vehicle (BEV). (4) PG-BEV pathway. The SNG from PG plant can be also used in a NGCC power plant to produce electricity first and then the generated power together with that produced in PG plant is used to drive BEV. Three main alternatives for this pathway are considered which include coal-BEV pathway, single SNG-SNGV pathway (SNG from the single product plant is used as vehicle fuel) and single SNG-BEV pathway (SNG from the single product plant is used for electricity generation first and the power is used to drive BEV). All the coal-based SNG and power cogeneration pathways and their competitive coal alternatives are shown in Figure 2.

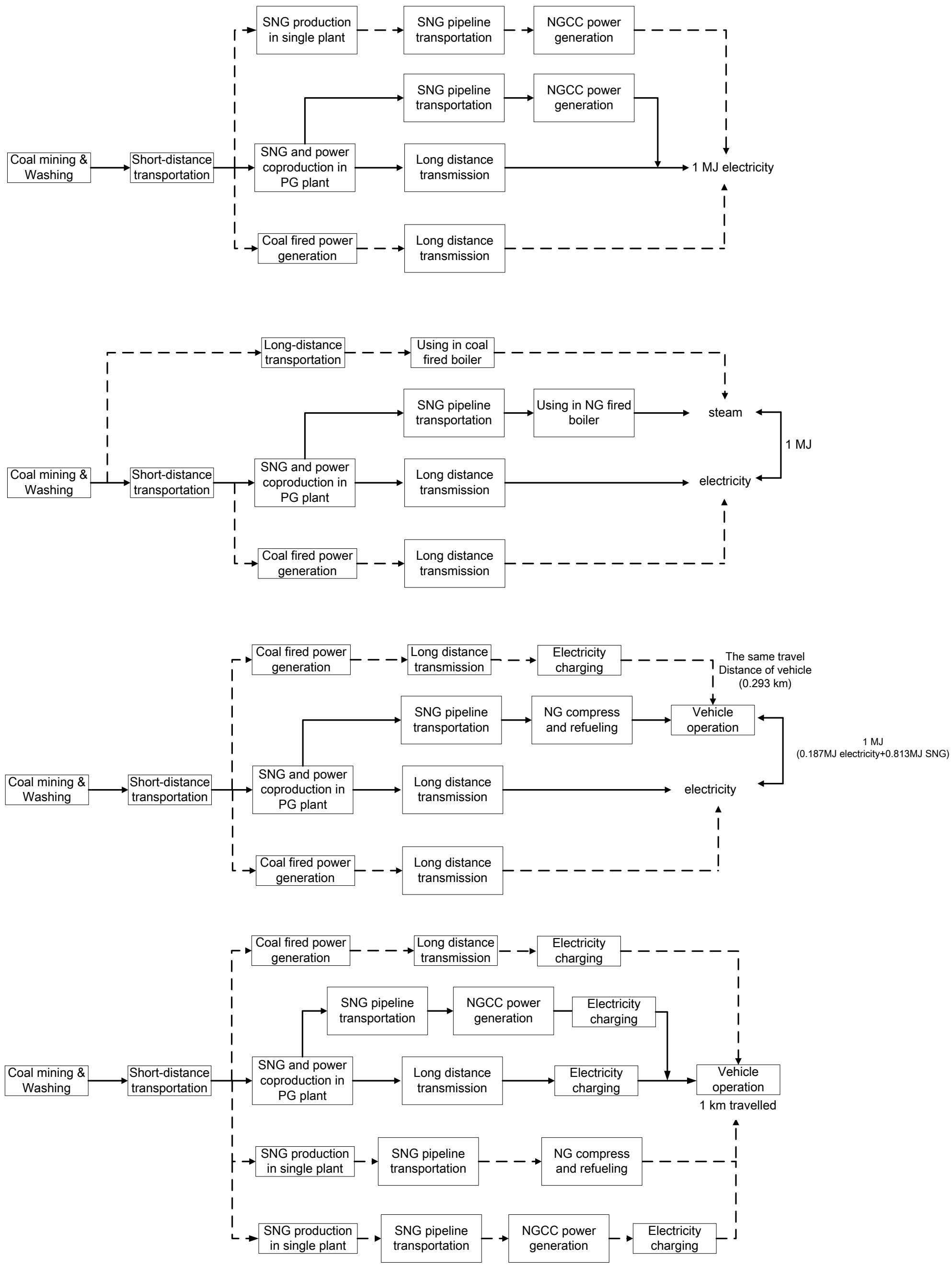


Fig. 2. *Scope definitions of coal-based SNG and power cogeneration and alternative coal pathways*

2.3–Life cycle assessment and scope definition

The scopes of the life cycle analysis of coal-based SNG and power cogeneration pathways and its competitive coal-based alternatives (represented as dash lines) are defined in Figure 2. The life cycle energy use is a summation of upstream and downstream energy consumption, which includes end-use energy output itself. Life cycle energy use is calculated using Eq. (1).

$$Life\ cycle\ energy\ use = \sum_{j=1}^{k}\sum_{i=1}^{n} E_{i,j} \qquad \text{Eq. (1)}$$

Where, $E_{i,j}$ represents the consumption of i_{th} type energy in the j_{th} sub process. The energy type may include electricity consumption, coal consumption, gas consumption etc., and varies from process to process. The sub process (e.g. coal mining) of each pathway has been defined in Figure 2.

Correspondingly, GHG emissions related to energy use are considered. According to the definition of IPCC report, GHG emissions related to energy use include those arising from fuel combustion and fugitive releases during fuel production or transportation. The life cycle GHG emissions are calculated in Eq. (2).

$$Life\ cycle\ GHG\ emissions = \sum_{j=1}^{k}\sum_{i=1}^{n}\sum_{m=1}^{3} GWP_m * E_{i,j} * EF_{i,j,m} + \sum_{j=1}^{k} GWP_m * FEF_m \qquad \text{Eq. (2)}$$

Where, the first term in Eq. (2) represents the GHG emissions from fuel combustion, and the second item represents the fugitive GHG emissions. GWP_m is the global warming potentials of individual gas m relative to CO_2, and $EF_{i,j,m}$ is the emission factor of m_{th} greenhouse gas related to i_{th} type energy consumption in the j_{th} sub process. FEF_m is the fugitive emission factors. Three main greenhouse gases are considered in current study: CO_2, CH_4 and N_2O. And the life cycle GHG emissions are expressed as grams CO_2 equivalent (gCO_2-eq.). The GWP value is 25 for methane and 298 for N_2O according to the 4^{th} assessment report of the Intergovernmental Panel on Climate Change [13]. It is worth noting that when GHG emissions are calculated the energy consumption in power plants, coal or gas- fired boilers actually refers to the energy input.

It is worth noting that the scope of the life cycle analyses were limited to energy consumption and CO_2 emissions in the fuel cycle, and those during equipment manufacturing and infrastructure construction are not considered. If SNG is used for power generation, the life cycle energy use and GHG emissions of all pathways are calculated on a basis of 1 MJ electricity output. If SNG is used to generate steam, the function unit is defined as an output of 1 MJ energy of a combination of steam and electricity, and the ratio of the steam output to electricity output is decided by the type of the cogeneration technology and also the efficiencies of electricity transmission and gas-fired boilers. For SNG is used to drive vehicles, the function unit for PG-SNGV-power pathway is defined as an output of 0.187MJ electricity and 0.813MJ SNG sent to the end users, which sum up to be 1MJ. The competitive pathways for PG-SNGV-power pathway are assumed to provide the same electricity output and to drive the vehicle the same distance. However, for PG-BEV and its alternative pathways, the function unit is based on 1km travelling distance of BEV.

3. Model developments

The model consists of four modules to assess life cycle energy use and GHG emissions: (1) coal mining, washing, and transportation; (2) SNG production and pipeline transportation; (3) power generation; and (4) end-use equipment. The modules of this model cover processes of the whole fuel cycle from primary energy production to energy consumption in end-use equipment. The energy consumption data and GHG emission factor for each module are described below.

3.1. Coal mining, washing and transportation

In recent years, China produced more than 3.5 billion tons of coal each year [1]. 95% of coal mining production in China is subsurface mining [4], and about one quarter of the coal produced in China was cleaned and sorted in 2010 [12]. Based on the data in 2012 provided by the National Bureau of Statistics of China [14], mining and washing 1 t of coal consumes 71.7 kg raw coal, 24.1 kWh electricity, 0.64 kg oil (diesel oil dominates), and 0.21 m^3 natural gas.

In addition to the GHG emissions arising from fuel combustion, those due to fugitive emissions during coal mining and washing are considerable [15]. Fugitive GHG releases from coal mining include mining emissions, post-mining emissions, and emissions caused by low temperature oxidation and spontaneous combustion [15]. Methane is the main fugitive emission in the process of coal mining. It was reported that 7.0-10.0 cubic meters methane [16-17] and 6 cubic meters CO_2 were emitted for each ton of coal mined [18].

It is assumed that all coal-based power generation or SNG and power cogeneration plants are located near the coal mines, and coal is transported by diesel truck to these plants no more than 50 km [4]. For coal-steam pathway which requires long distance coal transportation, coal is transported through the combination of railway, waterway and highway [4]. It was reported that the average distance for long distance coal transportation is 640 km for railway, 1500 km for waterway and 500 km for highway [4]. The energy consumption for coal mining, washing & transportation is summarized in Table 1.

Table 1. *Energy consumption for coal mining, washing & transportation*

	Coal mining & washing [14]	Coal transportation by railway [4]	Coal transportation by waterway [4]	Coal transportation by truck [4]
Natural gas	0.21 m^3/t	-	-	-
Raw coal	71.7 kg/t	-	-	-
Diesel oil	0.64 kg/t	203 kJ/(t km)	-	1480 kJ/(t km)
Electricity	24.1 kWh/t	78 kJ/(t km)	-	-
Fuel oil	-	-	257 kJ/(t km)	-

3.2. SNG production from single product plant or SNG and power cogeneration plant, and SNG pipeline transportation

SNG can be produced in a single product plant in which SNG is the only product. The first coal to SNG project, known as Great Plains Synfuel Plant, was erected in North Dakota of USA. It was reported that the energy conversion efficiency of this plant was around 55% [5, 19]. In recent years, in order to enforce energy security and with the increasing price of NG in China, numerous coal to SNG plants have been constructed in China which can produces around 16 million cubic meters SNG per year. The efficiencies of these single SNG product plants were between 55.0% and 60.0% [5, 19-20]. However, some literature also reported a 50% efficiency of single SNG product plant [4, 21-22]. In this paper, it is assumed the energy conversion efficiency of a single product plant ranges from 50.0% to 60.0% with an average efficiency of 57.5%.

There are different types of coal-based SNG and power cogeneration plants. Based on the previous study, the efficiencies of the SNG and power cogeneration plants range from around 59.5% to 64.5% [8-11]. The specific efficiency of a cogeneration plant is decided by its structure and also the technical parameters applied in this plant. Different chemical to power output ratio (CPOR, ratio of the SNG lower heating value output to the power output) result in different plant efficiencies [8-11]. In this study, a plant with 64.3% efficiency corresponding to chemical to power output ratio of 4.06 is assumed based on previous study [8-11]. CO_2 emissions from the cogeneration plant include those from the flue gas of the combined cycle and also the releases of the water gas shift unit (if applicable). In the selected cogeneration plant, CO_2 emissions are 104.4 g/(MJ energy product) [8-11]. The fugitive GHG emissions in the cogeneration plant are negligible.

SNG transportation is similar to natural gas (NG) transportation. Long distance pipeline transportation of NG is preferable in China to transport NG from the west to the east. The total energy consumption of pipeline transportation is around 0.0285 m^3 gas/(1000 m^3 km) and 4.88×10^{-3} kWh electricity/(1000 m^3 km) [23]. Fugitive GHG emissions for gas transmission include 1.34 g CH_4 and 4.1 mg CO_2 per cubic meter marketable gas [15].

3.3 Power generation and transmission

In recent years, the installed capacity of coal-fired power plants has been decreasing but still dominates China's power generation. Coal-fired and NG-fired power plants accounted for 63.0% and 3.7% of the total 1.25 billion kilowatts installed power capacity in 2013, respectively [1].

In order to save energy and control pollutant emissions in China, small coal-fired power plants below 10 MW are forced to shut down in recent years. The main coal-fired power generation units in China are over 300 MW, accounted for over 70% of total coal-fired power generation units in 2011 [4]. The supercritical coal-fired power plants with capacity over 1000 MW are increasing rapidly in these years. Through improving the mainstream parameters of the generating units, the coal consumption of per kilowatt electricity supply is decreasing in these years. Based on the statistics provided by China Electricity Council (CEC), the average coal consumption of electricity supply was 321 gce/ kWh in 2013 [24]. The efficiencies of the coal-fired power plants are relevant to the steam temperatures and pressures. The net efficiency of power supply is enhanced to 40-42% for supercritical units, and 43-45% to ultra supercritical (USC) units [25-26].

Gas-fired power plants have a typical capacity of 180MW and 350MW in China. Based on a survey of 119 NGCC power plants which accounted for 98% of gas-fired power generation capacity, the power supply efficiencies of these plants could reach 50%-55% [4]. Equipped with H-Class gas turbines with higher inlet temperature, the efficiency of the NGCC power plant is proven to reach 61% [27]. However, it has been proved that the efficiency of the NGCC power plant is relevant to the parameters such as capacity factor (CF) and the gas turbine inlet temperature [28-29]. Low CF may result in low power supply efficiency of the NGCC power plant, but current study did not consider such influences. In current study, an average power supply efficiency of the NGCC power plants in China is assumed as 55.5%.

Electricity loss during long distance transmission in recent years dropped from around 7.04% in 2006 to around 6.49% in 2010, based on the data released by State Electricity Regulatory Commission (SERC) [30-31]. The target of the transmission loss rate is 6.3% in 2015 [32]. It is assumed the power loss rate during its transmission is 6.3% in this paper.

3.4 End use equipments

Coal-fired and gas-fired boilers are two types of boilers used for generating heating or industry steam. The efficiency of coal-fired boilers was between 55% and 75% with an average of 65% [4], and the efficiency of gas-fired boilers was between 80% and 85% with an average of 82.5% [33].

In China, CNG that is used as the fuel of city buses and passenger cars comes from conventional natural gas, LNG, and coal-based SNG. In this paper, a car with five passengers is selected as a typical CNG driven vehicle. According to the data provided by the producer, its CNG consumption is around 7.7 m^3/100km. Battery electric vehicle (BEV) powered by electricity from coal-fired power plants is a competitive alternative to the CNG car fueled by coal-based SNG. It was reported that the energy consumption for an electric car was 20kWh/100km on average, although it could be around 15 kWh/100km for electric cars made by some international OEMs [4]. The fast charging loss is assumed to be 10% at the BEV charging stations [4]. The energy efficiencies of key fuel conversion processes are summarized in Table 2.

Table 2. *Energy efficiencies of key fuel conversion processes in this paper*

	Efficiency (average level)	Lower	Upper
Coal-fired power plant (average)	38.2%	38.2%	38.2%
Coal-fired power plant (supercritical)	41.0%	40.0%	42.0%
Coal-fired power plant (USC)	44.0%	43.0%	45.0%
NGCC plant	55.5%	50.0%	61.0%
Coal-fired boilers	65.0%	55.0%	75.0%
NG fired boilers	82.5%	80.0%	85.0%
Coal to SNG-single product plant	57.5%	50.0%	60.0%
SNG and power cogeneration	64.3%	64.3%	64.3%
	Energy consumption		
BEV	20kWh/100km		
SNGV	7.7 m^3/100km		

3.5 Emission factors for different energy process

GHG emissions only related to fuel cycle are considered in this paper. The emission factors of coal, natural gas and diesel combustion are based on the IPCC assessment, which are reported in Table 3 [15]. It is assumed that the electricity is generated from coal power plants, and thus the emission factor for electricity is calculated as 251.57 g/MJ. The emission factors of fugitive GHG emissions are summarized in Table 4 [15].

Table 3. *GHG emission factors of fuel combustion for different processes [15]*

	CO_2	CH_4	N_2O	Units	Application process
Natural gas/SNG	56100	1	1	kg/TJ energy input	Industrial boilers
Natural gas/SNG	56100	92	3	kg/TJ energy input	Vehicle engines

Natural gas/SNG	56100	1	3	kg/TJ energy input	Combined cycle
Sub-bituminous	96100	1	0.7	kg/TJ energy input	Industrial boilers
Sub-bituminous	96100	0.7	0.5	kg/TJ energy input	Pulverized power plant
Diesel	74100	3.9	3.9	kg/TJ energy input	Car vehicle engines
Diesel	74100	4.15	28.6	kg/TJ energy input	Railway transportation
Fuel oil	77400	7.0	2.0	kg/TJ energy input	Water-borne navigation
Electricity	251.57*	NA	NA	g/MJ-electricity	

*Electricity is assumed to be produced from a coal-fired power plant.

Table 4. *Emission factors of fugitive emissions [15]*

	CH_4	CO_2	N_2O	Units of measure
subsurface coal mining	7.0-10.0	NA	NA	m^3/ton
Gas transmission, storage & distribution	133.5×10^{-5}	40.9×10^{-7}	NA	kg/ m^3 of marketable gas

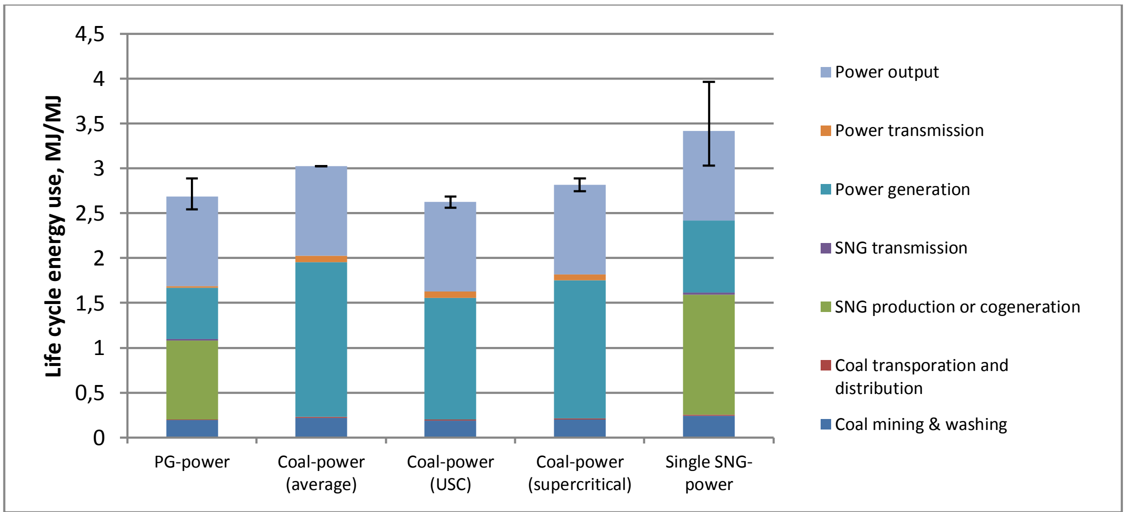
4. Results and discussions

The life cycle energy use and GHG emissions of different pathways of the coal-based SNG and power cogeneration technology and its competitive alternatives are compared and discussed below.

4.1. Power generation pathways

Results of PG-power pathway and its four competitive coal alternatives are summarized in Figure 3. If SNG is produced from a single product plant, its life cycle energy use for providing 1MJ electricity to the end users ranges from 3.03-3.96 MJ, the lower limit of which can be comparable to 3.02 MJ for average coal-power pathway but is still higher than 2.75-2.89 MJ for supercritical and 2.56-2.69 MJ for USC coal-power pathways due to the large energy consumption in single SNG production process. However, if SNG is produced from a PG plant instead of a single product plant, its life cycle energy use is decreased to 2.54-2.89 MJ with an average of 2.79 MJ. Due to the high efficient cogeneration of power and SNG, the life cycle energy use for PG-power pathway is typically lower than supercritical coal-power, but is still 1.6% higher than USC coal-power pathway.

Correspondingly, the life cycle GHG emissions of PG-power pathway range from 266-310 gCO_2 eq. /MJ, the average of which are lower than those of all coal-power pathways including USC units. Power transmission generates higher GHG emissions than SNG transportation due to a lot of CO_2 emissions brought by its power losses, and therefore the average GHG emissions of PG-power pathway is slightly lower than USC coal-power pathway although it has a slightly higher life cycle energy use. For coal-power pathways, power generation dominates the whole emissions, while for PG-power and single SNG-power pathways emissions from PG plant/SNG production and NGCC power generation are both the main contributors.



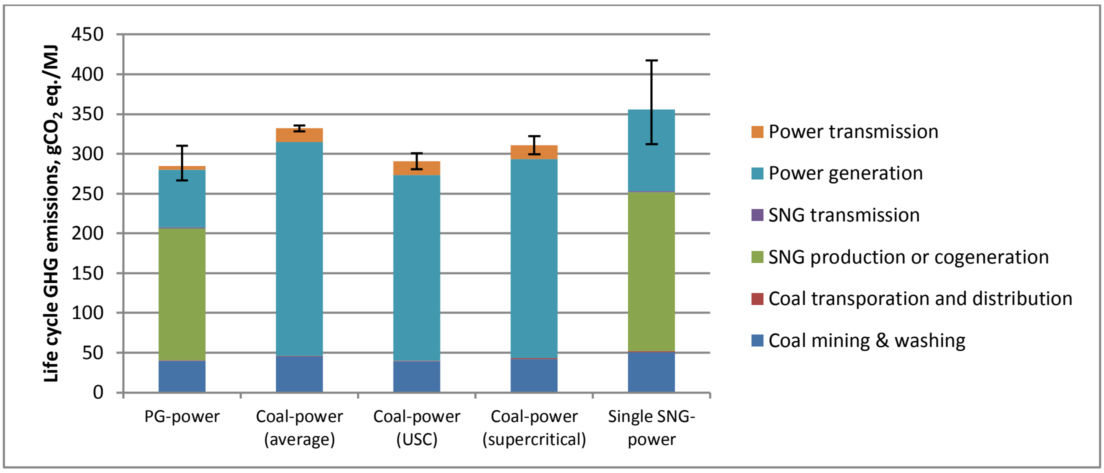


Fig. 3. *Life cycle energy use and GHG emissions of PG-power and its competitive pathways*

4.2. Steam and power cogeneration pathways

Results of four steam and power cogeneration pathways are illustrated in Figure 4. To provide 1MJ electricity and steam (0.78 MJ steam and 0.22 MJ electricity), the average life cycle energy use is 2.00 MJ for PG-steam-power pathway with a range of 1.95-2.05 MJ, 2.04 MJ for combined coal-steam and coal-power (average) pathway with a range of 1.85-2.30 MJ, 1.99 MJ for combined coal-steam and supercritical coal-power units with a range of 1.79-2.27 MJ, and 1.95 MJ for combined coal-steam and USC coal-power units with a range of 1.75-2.22 MJ, respectively. Due to much higher efficiency of SNG-fired boilers than coal-fired boilers and the benefit from SNG and power cogeneration, the life cycle energy use of PG-steam-power cogeneration pathway is basically comparable to these combined coal-steam and coal-power pathways.

The life cycle GHG emissions of PG-steam-power cogeneration pathway have a range of 204.3-219.1 with an average value 211.5 gCO_2 eq. /MJ, which are also comparable to coal-power pathways. For each pathway, the total emissions are dominated by the sum of power generation/cogeneration and fuel combustion in boiler.

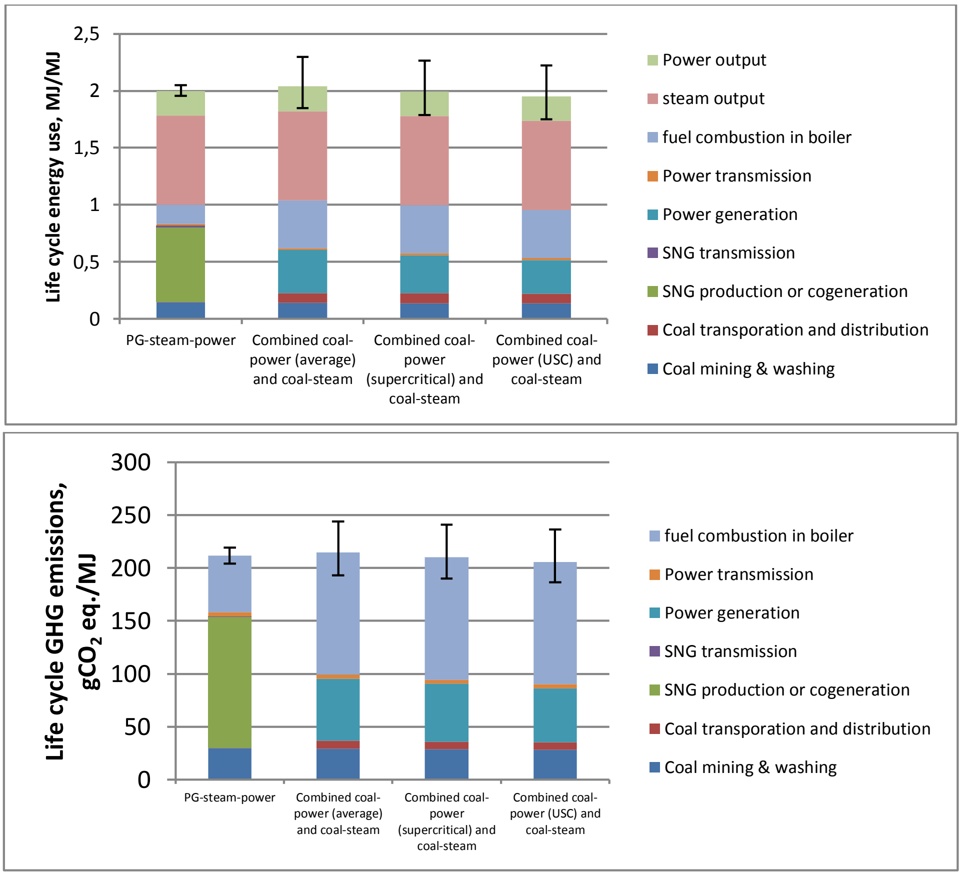


Fig.4. Life cycle energy use and GHG emissions of PG-steam-power and competitive pathways

4.3 Vehicle operation and power generation pathways

Since SNG and power are two products in cogeneration plant and SNG can be used to drive passenger car, vehicle operation and power cogeneration pathways are considered in this paper. For PG-SNGV-power pathway, the electricity and SNG generated from PG plant is transmitted to urban area, and then SNG is used to drive cars. The reference base for PG-SNGV-power pathway is 0.187MJ electricity and 0.813MJ SNG sent to the end users, which sum up to be 1MJ. It is assumed that all other pathways produce the same electricity to the end users and the power from the alternative pathway can drive the same car for the same distance with PG-SNGV-power pathway. As shown in Figure 5, the SNG driven car consumes much higher energy (around 2.77MJ/km) than the electricity driven car (0.719MJ/km) for the same travelling distance, resulting in the life cycle energy use of PG-SNGV-power pathway is 1.72 MJ/(0.187MJ electricity+0.293km car travelling) and is much higher than all combined coal-BEV and coal- power pathways.

Correspondingly, the life cycle GHG emissions of PG-SNGV-power pathway range from 182-186gCO_2 eq./(0.187MJ electricity+0.293km car travelling) and are also higher than all other competitive alternatives. PG plant is the largest emitter and followed by the vehicle operation for PG-SNGV-power pathway. For other coal alternatives, emissions from power generation are the main contributor.

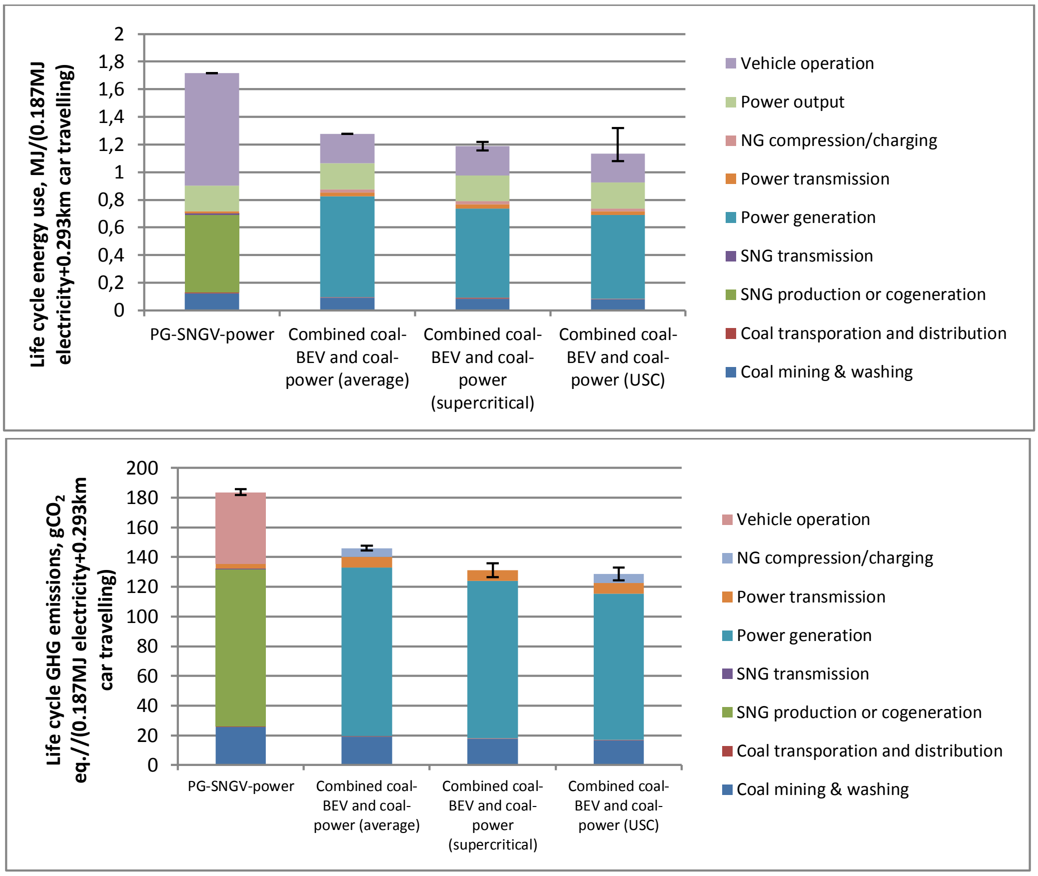


Fig. 5. *Life cycle energy use and GHG emissions of PG-SNGV-power and competitive pathways*

4.4 Pure vehicle operation pathways

Differently from PG-SNGV-power pathway, in the PG-BEV pathway the SNG produced from PG plant is sent to generate electricity in NGCC power plant first and then the electricity is used to drive passenger car. The reference base is 1km car travelling distance. As shown in Figure 6, the life cycle energy use of 2.03-2.31 MJ/km, which is much lower than single SNG-BEV (2.42-3.17 MJ/km) or single SNG-SNGV (5.04-5.49 MJ/km) pathway and is lower than coal-BEV (average) pathway. Due to the high efficient cogeneration of SNG and power in PG plant, the life cycle energy use of PG-BEV pathway can be slightly lower than supercritical coal-BEV pathway and is around 2.4% higher than USC coal-BEV pathway.

The average life cycle GHG emissions of PG-power-vehicle pathway is 248 gCO_2 eq./km with a range of 233-268 gCO_2 eq./km, which are lower than the average level of 286 gCO_2 eq./km for coal-BEV (average), 268 gCO_2 eq./km for supercritical coal-BEV, and 253 gCO_2 eq./km for USC coal-BEV pathways. For single

SNG-BEV pathway, the lower limit of its life cycle GHG emissions (270-354 gCO_2 eq./km) are comparable to coal-BEV (average) pathway. For single SNG-SNGV pathway, its life cycle GHG emissions are 525-585 gCO_2 eq./km that are obviously higher than all coal-BEV pathways due to large energy consumption both in SNG production process and in vehicle operation process.

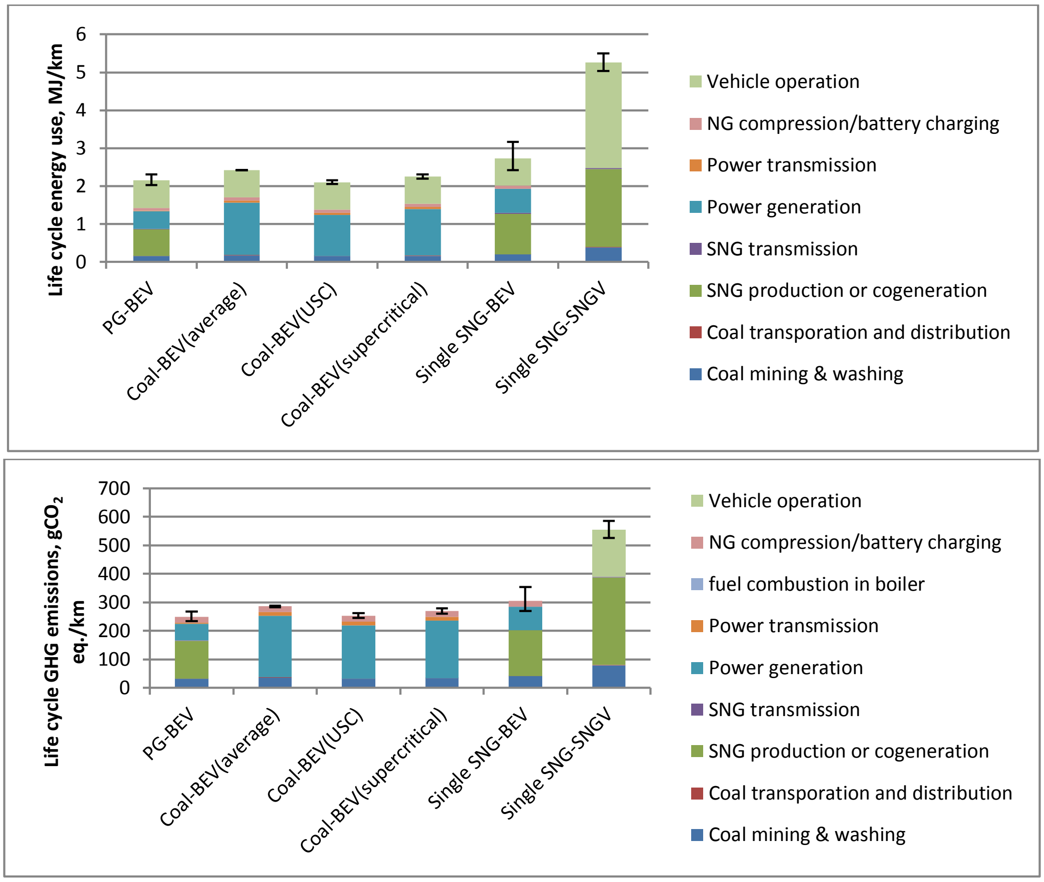


Fig. 6. *Life cycle energy use and GHG emissions of PG-BEV and competitive pathways*

5. Conclusions and implications

Coal-based cogeneration/polygeneration technologies are thought as an efficient way to produce both alternative fuels and electricity. This paper presents life cycle energy use and GHG emissions for coal-based SNG and power cogeneration technology, and the results show:

(1) If SNG is produced from a single product plant, the lower limit of its life cycle energy use and GHG emissions for providing 1MJ electricity to the end users are comparable to average coal-power pathway but is still higher than supercritical and USC coal-power pathways due to the large energy consumption in single SNG production process.

(2) If SNG is produced from a PG plant, the life cycle energy use for PG-power pathway is typically lower than supercritical coal-power, but is still 1.6% higher than USC coal-power pathway. Its life cycle GHG emissions range from 266-310 gCO_2 eq. /MJ, the average of which are lower than those of all coal-power pathways including USC units.

(3) If SNG is used for steam generation, the life cycle energy use and GHG emissions of PG-steam-power cogeneration pathway are basically comparable to these combined coal-steam and coal-power pathways.

(4) If SNG is used to drive vehicle car, the life cycle energy use and GHG emissions of PG-SNGV-power pathway are both much higher than all combined coal-BEV and coal-power pathways, due to much higher energy consumption in a SNG driven car than in a BEV car.

(5) If SNG is used to generate electricity first and the produced power is used to drive BEV car, the life cycle energy use of PG-BEV pathway can be slightly lower than supercritical coal-BEV pathway and is around 2.4% higher than USC coal-BEV pathway. And the average life cycle GHG emissions are lower than those of all coal-BEV pathways.

As China's energy structure is highly coal dependent, how to convert coal into clean alternative fuels efficiently is an important issue. Current coal to SNG technology in a single production plant does not show advantages over coal power pathways in terms of life cycle energy efficiency and GHG emissions, however, it may have lower life cycle energy use and lower GHG emissions with the technology progressing. Therefore, when energy security and its energy efficiency improvement potentials are both considered, it is recommended that coal to SNG technologies can be developed to provide natural gas to the cities where coal consumptions are strictly restrained.

The coal-based SNG and power cogeneration technologies are more attractive. The findings in this paper indicate that coal-based SNG and power cogeneration technologies have comparable energy performances and lower GHG emissions over other coal alternative pathways such as coal-power and coal-BEV, and may play an important role in the energy sector of China. The early demonstrations of such cogeneration plants are recommended to be supported with a priority.

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