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Life cycle analysis of coal-based synthetic natural gas for heat supply and electricity generation in China

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ABSTRACT

In the present paper, life cycle analysis of coal-based synthetic natural gas (SNG) is performed for heat supply and electricity generation in China with a full consideration of energy efficiency, environmental pollutions and greenhouse gas emissions. Several different technical routes of SNG are studied in detail and the emissions of SO_2, NO_x, CO_2 and energy efficiency are all calculated. For comparisons, technical routes of ultra supercritical and coal-fired power generations are also analyzed together with a direct use of coal for heat supply. Our results show that the cogeneration of heat and electricity is a suitable technical route for SNG utilization. Comparing with ultra-supercritical and coal-fired power generations, technical routes based on SNG could significantly reduce the emissions of pollutants (especially for heat supply) with an acceptable level of the energy efficiency. After synthesis of SNG, our life cycle analysis suggests that SNG should be transported to the energy demand center for further power generation locally.

1. Introduction

In China's energy system, coal plays an important role in the energy supplying (e.g. in terms of electricity generation Wang and Li, 2016; Yuan et al., 2014). Although the renewable energies (e.g. wind energy Liao, 2016; Zhang et al., 2016a, solar energy Urban et al., 2016, hydro energy Chen et al., 2016; Zhang et al., 2018, 2016b, tidal energy Chang and Wang, 2017; Huang et al., 2017; Huang and Kanemoto, 2015 and pumped energy storage Zhang et al., 2017a,b) are developing very fast in China, coal will still be a paramount natural resource in the energy system according to the long-term planning up to 2050 (Zhou et al., 2013; Zhang et al., 2017c) with massive integration of renewable energies (Davidson et al., 2016). Critical problems of coal-based energy generation systems are the environmental pollutions (e.g. SO_2 and NO_x emissions) and the tremendous generations of carbon dioxide. Hence, natural gas power generations are being developed very fast in China, providing a clean technique for the energy supply. However, in China, the resources of the natural gas are quite limited, leading to great challenges on the stable supply of natural gases. Although oil-based energy supply system has achieved big successes in western counties (e.g. USA), it is not suitable for China's energy system because the resources of oil in China are too limited to support the energy security of the whole country. Based on the China's case, one of the solutions for clean energy supply is to develop coal-based chemical industry e.g. the pro-

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duction of methanol (Li et al., 2010; Uddin et al., 2015) and synthetic natural gas (SNG) (Yang and Jackson, 2013). Generally speaking, coal-based SNG could not only provide high-quality natural gases for energy systems but also with low pollutions (Chinese Academy of Engineering, 2017).

Fig. 1 shows a detailed process of a typical coal-based synthetic natural gas project. Generally, with high temperature, coal will react with oxygen and water vapor, generating syngas. Through gasification, purification, methanation and other processes, synthetic natural gas will be produced. The main production processes of coal-based SNG include coal gasification, crude gas conversion, purification, methane synthesis and other technological units together with auxiliary equipment including the air separation, thermal power stations, sulfur recovery devices and so on. By the end of 2016, in China, there are three coal-based SNG demonstration projects commissioned and eight projects under construction or plan. The total SNG productions of all projects is about 25 billion cubic meters per year (Chinese Academy of Engineering, 2017). As the SNG industry could also generate pollutions, a rigorous evaluation of the full cycle of coal-based SNG (from the coal mining to the terminal energy) should be performed based on the life cycle analysis (LCA). In the present paper, our investigations focus on the LCA of several typical coal-based SNG technical routes.

In the literature, LCA has been widely employed for the investigations of energy systems including Marcellus shale supply chains (Gao and You, 2017a, 2015), photovoltaic technologies (Yue et al., 2012, 2014), alternative vehicle fuels (Ou et al., 2012, 2013, 2010a,b), bioethanol production (Zhao et al., 2016), hydrocarbon biorefinery (Gebreslassie et al., 2013). Specifically, LCA has been also intensively applied into the evaluations of the coal chemical engineering techniques e.g. coal-to-methanol (Li et al., 2010), coal-to-olefins (Gao et al., 2018a), and coal-to-liquid (Gao et al., 2018c). Gao et al. (2018a) performed LCA of the China's largest coal-based methanol-to-olefins project. Both the pollutant emissions and water consumptions of the project were all evaluated based on the reliable data. Through the analysis, they quantitatively identified the water and energy saving potentials of the given technical route. Gao et al. (2018c) investigated several typical coal liquefaction routes including direct and indirect coal liquefactions based on LCA. Different transportation methods and liquefaction factory locations are discussed in detail with cost analysis. About the theoretical method, Gao and You (2017b) introduced the game theory approach into the shale gas supply chains through considering both the economics and life cycle greenhouse gas emissions. They converted the problem into a multiobjective mixed-integer bilevel linear programming one, which was solved based on an efficient projection-based reformulation and decomposition algorithm. Ou et al. (2011) analyzed the primary energy consumption and greenhouse gas emissions of the power generation and distribution in China. Ou et al. (2012) calculated the fossil energy consumption and greenhouse gas emissions of major alternative vehicle fuels through LCA and made a comparison with conventional fuels. Compared with gasoline vehicles, they concluded that the reduction of greenhouse gas emissions of vehicles powered with natural gas or liquefied petroleum gas is significant. Yi et al. (2015) reviewed the advanced techniques of coal chemical engineering for the reduction of CO_2 emissions in the carbon cycle. Yi et al. (2012) proposed a new optimization method for the poly-generation system integration with a high energy efficiency and element conversion efficiency of CO_2/CH_4. Cheng et al. (2015) proposed a multi-region optimization planning model for China's power system planning. Zhang et al. (2013a,b) introduced the multi-period optimization model into the planning of China's power sector with full consideration of the mitigation of carbon dioxide. In the literature, life cycle analysis of the coal-based SNG is still absent with full consideration of economics (e.g. energy efficiency), pollutions and CO_2 emissions.

In the present paper, life cycle analysis of coal-based synthetic natural gas is performed for heat supply and electricity generation in China. Several different technical routes of SNG are studied in detail and the emissions of SO_2, NO_x, CO_2 and energy efficiency are all calculated. For comparisons, technical routes of ultra supercritical and coal-fired power generations are also analyzed together with a direct use of coal for heat supply. The sessions of the present paper are organized as follows. Section 2 introduces the modelling details, basic research methods and equations of the life cycle analysis. Section 3 compares the emissions and energy efficiency of several technical routes based on SNG with other possible coal-based technical routes. Section 4 concludes the main findings with perspectives.

2. Modelling and methods

In this section, modelling details and methods of the life cycle analysis are introduced in detail. Generally speaking, life cycle analysis is an analytical tool for evaluating the environmental impact and energy use of a product, process or activity in its entire life cycle. It is a method assessing all the inputs and outputs of a product during its full life cycle as well as its potential impacts on the environment. In general, the whole life cycle of a product is divided into several processes, such as mining, production and transportation of raw materials, facility construction, product manufacturing and processing, product transportation and sales, product use and consumption. According to the specific industries and products investigated, the divisions of the process could be very different. In the present paper, the division methods of the whole process proposed in our recent work (Gao et al., 2018c) were adopted for the convenience of consistence.

In the present paper, our attention is focused on the coal-based SNG technical routes. For the convenience of comparisons, the boundaries (e.g. start and terminal boundaries) of various kinds of the technical routes should be exactly the same and the entire process of the given technical route (from the coal mining to the terminal energy) should be all involved. Considering the paramount utilization of coal, the terminals of the present paper include heat and electricity.

2.1. *Energy efficiency of life cycle analysis*

In the present paper, the energy efficiency (η) of the life cycle analysis of a technical route is defined as (Gao et al., 2018c):

$$\eta = \frac{E_{end}}{E_{tot}}, \tag{1}$$

with

$$E_{tot} = EL_{min} + EL_{tra} + EL_{pro} + EL_{dis} + EL_{uti} + E_{end}. \tag{2}$$

Here E_{end} is the final output of heat (MJ) or electricity (with the unit MJ either for the convenience of comparisons) or both in the given technical route; E_{tot} is the total amount of the input primary energy, which consists of six parts as shown in Eq. (2); EL_{min}, EL_{tra}, EL_{pro}, EL_{dis} and EL_{uti} represent energy loss ("EL") during the processes of coal mining, coal transportation, production, distribution and terminal utilization respectively with three initial letters of the name of the processes being adopted as the subscripts in Eq. (2). In the following parts, the same subscripts are also adapted to represent the related parameters of each processes.

The calculation process of above five parameters shown in Eq. (2) are very similar. Hence, only a detailed process for the calculation of EL_{pro} will be shown here as follows

$$EL_{pro} = (DEL_{pro} + IEL_{pro})\,\alpha_{pro}, \tag{3}$$