Fuel Processing Technology 169 (2018) 42–49

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Life cycle analysis of direct and indirect coal liquefaction for vehicle power in China

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A R T I C L E I N F O

Keywords:
Coal chemical engineering
Life cycle analysis
Coal liquefaction
Coal-to-liquid
Energy efficiency
Production costs

A B S T R A C T

In the present paper, life cycle analysis of several typical coal liquefaction technical routes for vehicle power in China is performed with full considerations of environmental pollutants (e.g. SO_2 and NO_x), greenhouse gas emissions, costs, and energy efficiency. Direct and indirect coal liquefactions are discussed in detail with comparisons of several different technical routes (e.g. different transportation methods and liquefaction factory locations). Furthermore, sensitivity analysis of three direct coal liquefaction routes is performed with a focus on the transportation distance and vehicle internal combustion engine efficiency. Our analysis shows that the direct coal liquefaction with railway distribution is the best technical route among all the routes investigated, which could significantly reduce the emissions of CO_2, the production costs with acceptable energy efficiency. Generally speaking, the coal liquefaction factory should be located at the coal mining area to minimize the costs of products.

1. Introduction

Coal occupies the largest percentage in China's energy configuration (e.g. electricity generation). Although the renewable energies (e.g. wind [1], solar, and hydro [2] energies) and large-scale electrical energy storage [3,4] are being rapidly developed in China, coal will still be the primary energy resource in the next 50 years because of its huge reserves with plenty of utilizations. The primal problems of coal-based energy generations are the environmental pollutant emissions (e.g. SO_2 and NO_x emissions) and the carbon dioxide. However, coal liquefaction techniques could convert coal into oil and other important chemical products with limited environmental pollutions. As there is an increasing demand of the petroleum in China, coal liquefaction industry is increasing with an expeditious speed in China [5–8], providing a practical way to solve the intense problem of petrol supply with less emissions and relatively low costs [9]. In the present paper, several typical coal liquefaction technical routes (from the coal mining to terminal utilization) are evaluated with the aid of life cycle analysis (LCA [10]).

In the literature, LCA has been widely utilized into the analysis of the impacts of the energy utilization processes on the environments e.g. chemical catalyst [11,12], biofuel or biodiesel production [13–15], renewable energy [16–18], building carbon emissions [19–21], substitutable vehicle energy [22,23], coal-to-methanol process [24,25]. Ou et al. [26] utilized LCA to analyze the energy consumption and the carbon emissions of coal combustion with a focus on the China's cases. Zhai et al. [27] employed LCA to evaluate the coal-fired power system with solar energy input and heat storage device. Li et al. [28] investigated energy consumption and greenhouse emissions of the coal-based synthetic natural gas (SNG) and power cogeneration. They analyzed several technical routes of SNG and concluded that coal-based SNG and power cogeneration can reduce the energy consumptions and carbon emissions. Qin et al. [24] combined LCA with ASPEN plus simulation software to evaluate the carbon trace of the coal-to-methanol production process. Yi et al. [29] performed a comprehensive literature review on the carbon recycle of the coal chemical engineering and explored the way of reducing its emissions. In the heat supply system, Wang et al. [30] compared the greenhouse gas emissions and the pollutants releasing between the coal and the wood pellets together with the economics. Bartolozzi et al. [18] explored the impacts of the renewable energy on the environment during heating and cooling services. However, according to the literature review, LCA of the coal liquefaction has not been fully addressed especially to supply the vehicle power.

In the present paper, life cycle analysis of the coal-to-liquid (CTL) is performed to evaluate the impacts and economic potentials of the direct

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http://dx.doi.org/10.1016/j.fuproc.2017.09.007
Received 1 July 2017; Received in revised form 12 September 2017; Accepted 13 September 2017
Available online 21 September 2017
0378-3820/

and indirect coal liquefaction techniques. Several different technical routes of CTL are discussed in detail with focuses on the emissions of SO_2, NO_x, CO_2, costs and energy efficiency. The following sessions of the present paper are organized as below. Section 2 introduces the coal-to-liquid techniques, modeling details and basic equations of the life cycle analysis. Section 3 compares the emissions, costs and energy efficiency of several typical technical routes based on CTL with different transportation options. Section 4 concludes the main findings with limitations and perspectives.

2. Modeling and methods

2.1. Brief introduction of the coal-to-liquid

In this section, a brief introduction of the coal-to-liquid technique will be given. Comparing with oil, the percentage of H atom and ratio between H/C atoms of the coal are relatively low while the percentage of O atom of the coal is high. Hence, in the coal, the molecular weights of coal (e.g. sometimes larger than 1000) are much larger than those of oil (with averaged values being 200). Through coal liquefaction, the chemical structure of coal will be modified and finally various kinds of the oils (e.g. gasoline and diesel) are achieved with other useful products (e.g. liquefied petroleum gas and benzene). One of advantages of the coal-to-liquid is the remove of hazardous substance e.g. sulfur atom, which will generate emissions of SO_2 during the coal combustion.

Depending on the technique routes, the coal-to-liquid could be categorized as direct and indirect techniques. For the direct coal-to-liquid technique, the process is simple with low cost. And, the temperature and pressure required for the route are high (about 400–450 °C and 20–30 MPa). For the indirect coal-to-liquid technique, the process could be utilized for various kinds of coals and the quality of products is high. For example, high-sulfur coal could be employed in the indirect route with converting sulfur atom in the coal into the elemental sulfur.

2.2. Basics of life cycle analysis

In this section, methods of the life cycle analysis of CTL process are presented. In the present paper, the whole process of the coal-to-liquid techniques is analyzed in detail. Both the energy efficiency and pollutant/CO_2 emissions are all considered. The aims of the present analysis are the identification of the competitive technical route from the viewpoint of the full cycle. Fig. 1 shows the detailed processes (from coal to the vehicle power) involved in the CTL process analyzed here. The entire process is divided into five sections: (coal) mining, transportation, production, distribution and final utilization. For the production process, both direct and indirection coal liquefaction techniques are considered with two different kinds of positions (local coal mining area and load demand center). For the distribution of the CTL products, truck through highway and railway are compared. For the definition of each technical route, readers are referred to Tables 1 and 2.

Table 1
A detailed description of direct and indirect coal liquefaction technical routes.

Abbreviation	Mining	Transportation	Production	Distribution	Utilization
DCL	Coal mining	Coal short transportation	Coal direct liquefaction	Truck long delivery and dispensing	Vehicle
ICL	Coal mining	Coal short transportation	Coal indirect liquefaction	Truck long delivery and dispensing	Vehicle

2.3. Life cycle analysis of energy efficiency

The total energy efficiency (η) of a given technical route in our life cycle analysis is defined as:

$$\eta = \frac{W_{end}}{W_{tot}}. \quad (1)$$

Here, W_{end} is the final energy output from internal combustion engine of vehicle in the given technology route (unit: MJ); W_{tot} is the total amount of the input energy in the whole process (unit: MJ), which could be calculated as:

$$W_{tot} = W_{\min} + W_{tra} + W_{pro} + W_{dis} + W_{uti} + W_{end} \quad (2)$$

Here, the subscripts represent the first three letters of the five processes in the technical route including coal mining ("*min*"), transportation ("*tra*"), production ("*pro*"), distribution ("*dis*") and terminal utilization ("*uti*") respectively together with the terminal power ("end"). As the calculation of the energy loss during each process is quite routine, the calculation of productions (W_{pro}) is taken as an example as follows:

$$W_{pro} = \frac{PEW_{pro} - 1 + SEW_{pro} + MCW_{pro}}{\eta_{ice}}, \quad (3)$$

with

$$SEW_{pro} = \sum_i \frac{SEW_{pro}^i}{\eta_i} \ (i\text{=electricity, diesel, etc.}), \quad (4)$$

$$MCW_{pro} = \sum_j [MC_{pro}^j \cdot (mw_j + mrw_j)] + CW_{pro} + CRW_{pro} (j \text{=steel, cement, etc.}). \quad (5)$$

Here, PEW_{pro} is the direct primary energy (e.g. coal) consumptions per unit product in the route; $SEW_{pro}{}^i$ is the direct secondary energy (electricity, diesel, etc.) consumptions per unit product in the route; MCW_{pro} is the sum of the three contributions: material consumptions, equipment/factory building and recovery; η_{ice} is the efficiency of the internal combustion engine; η_i is the energy conversion efficiency of the secondary energy production; $MC_{pro}{}^j$ is the material (steel, cement, etc.) consumptions per unit product in the route; mw_j and mrw_j represent the energy consumption per unit material during the material production

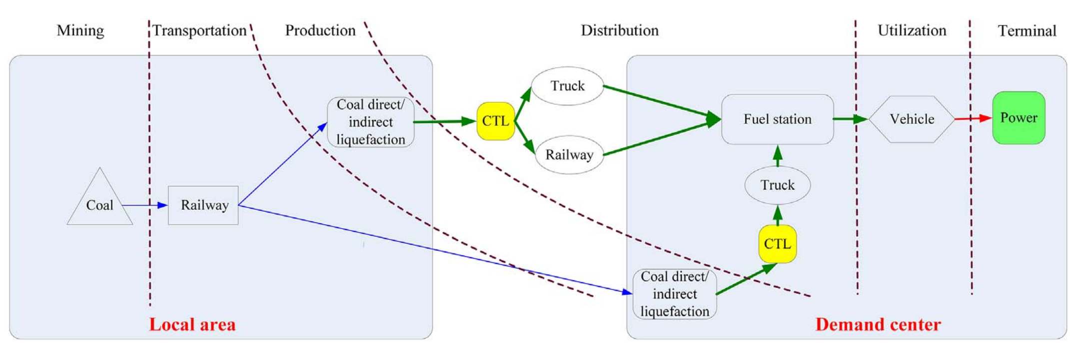

Fig. 1. A detailed description of different technical routes of direct coal liquefaction (DCL) and indirect coal liquefaction (ICL). The "CTL" in the figure refers to coal-to-liquid.