Renewable Energy 118 (2018) 870–878

Contents lists available at ScienceDirect

Renewable Energy

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

Sustainability assessment of synfuels from biomass or coal: An insight on the economic and ecological burdens

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ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form
22 July 2017
Accepted 23 November 2017
Available online 24 November 2017

Keywords:
Sustainability
Biomass-to-Liquid fuel
Coal-to-Liquid fuel
Production cost
Ecological Cumulative Exergy Consumption

ABSTRACT

Biomass-to-Liquid (BTL) and Coal-to-Liquid (CTL) Synfuels have been the two most significant alternatives for the transportation liquid fuels. But their performance in resource depletion, economic investment, and environmental impacts differs greatly from the conventional refinery. For comparing the strengths and the weakness of each alternative, a quantitative trade-off procedure is required. However, a few researches have discussed such trade-off procedures. In this paper, the life cycle inventories, production cost, and Ecological Cumulative Exergy Consumption (ECEC) of BTL and CTL in China are investigated to compare the pros and cons of each Synfuel. Herewith, the ECEC is taken as a metric for the ecological burden, providing a significant way to integrate the life cycle resource, economic, and environmental factors of Synfuels for the sustainability assessments. The results demonstrated that the shifting of petroleum to BTL reduced the CO_2 emission by 98% but relatively increased the water consumption and wastewater. The production cost-breakeven crude oil price with BTL is about 98 $/bbl without considering the taxes, and it could be decreased to 50 $/bbl according to China's tax policy. More importantly, BTL could cut as high as 65% of the overall ecological burden so that would be much more beneficial to the sustainable development of the fuel industry. On the other hand, the economic effectiveness of CTL is relatively reliable, where its production cost-breakeven crude oil price is below 70 $/bbl. However, 10.7 t of CO_2 are created for each tonne of CTL, which is 3.3 times to conventional petroleum, and three times of water is consumed in the whole. The ECEC analysis also indicates that the shifting of crude oil to coal for transportation fuels will almost double the overall ecological burden and pose threats to the safety and sustainability of the entire fuel industry at which the cautions should be paid.

1. Introduction

With the rapid development of China's economy, oil consumption has increased rapidly in recent years, to approximately 543 million tonnes in 2015, of which 60% of the oil was imported [1]. Due to the prospect of oil price fluctuation and unstable supply, interests in securing oil and other alternatives have been intensifying for satisfying the needs of transportation liquid fuels. Biomass and coal are the most significant alternatives to oil to fulfill these issues, with technologies such as Fischer-Tropsch (FT) fuels, bioethanol, and bio-diesel [2]. Among them, FT fuels have emerged as a promising alternative because they are directly used to replace the petroleum fuel without any significant changes in the distribution infrastructure or vehicle engines [3,4].

Biomass, coal, and natural gas are converted to syngas from which FT fuels are synthesized [3,5], and are called Biomass-to-Liquid (BTL), Coal-to-Liquid (CTL), and Gas-to-Liquid (GTL) fuels, respectively. Although conceptually appealing, GTL is not an applicable solution for China. China lacks natural gas resource, and GTL also runs against its policies. Biomass is a renewable resource that can be used for liquid fuels production. Generally, the sources of biomass are classified as food or non-food. Since the use of food biomass may increase the food price and lead to the significant net CO_2 emission [6,7], recent researches of BTL have been focusing on non-food biomass such as wood chips and straws among others [5,8]. According to Cai et al. [9], there had been 634 million tonnes/year of collectible straws in China. After partly returned to soil as

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https://doi.org/10.1016/j.renene.2017.11.073
0960-1481/

fertilizers, animal feeding, house cooking and heating, and other industrial use, there were still a significant amount of straws (23.9%) left over that could not been utilized [9]. These leftover straws are currently burned in the field for nothing but resulting in the severe air pollution [10]. Recently, the Chinese government has been trying to deal with these issues [11]. Making the straws biomass into transportation fuels offers a great potential in abating this plight as well as reduce the dependence on oil.

CTL is another alternative of the transportation fuels. The major advantages of coal include its abundant reserves and availability at a relatively low price. In China, the annual production of coal is more than 3.7 billion tonnes [12], and the current coal price is only 250–450 CNY/tonne [13] (*i.e.*, 475–855 CNY/tonne of oil equivalent). Shifting from oil to coal for the production of transportation fuels may probably cut down the cost and ensure the stable supplies.

However, the rationalities of BTL and CTL technologies are still in a heated debate [14,15]. Larson et al. [5] investigated the CO_2 emission and economic feasibility of BTL and CTL in Illinois, America, demonstrating that both the alternatives have their own pros and cons. They have pointed out the high production cost in BTL and the serious CO_2 emission in CTL. In another study, Yang et al. [3] explored the various performances of BTL and CTL processes by 10 disaggregated indicators such as energy efficiency and renewability. Their work resulted in a spider diagram, which featured out the pros and cons of each alternative. However, these reports still lack a systematic, quantitative trade-off procedure to compare the strengths of each alternative with its corresponding weaknesses. From the ecological point of view, the overall sustainability of BTL and CTL have not yet been assessed or compared on a consistent base, which may confuse the policy makers in decision-making.

In a way, the Analytic Hierarchy Process [16], one of the most popular methods to establish trade-off among the multi-objectives, is capable of integrating different objectives into a final manageable metric for overall assessments. However, it is inseparable from a certain arbitrary weighting offered by selected experts, thus leading to the doubts on its rationality and scientific base. To overcome the issue of arbitrary weighting, the Ecological Cumulative Exergy Consumption (ECEC) analysis was proposed by Hau et al. [17] based on the Emergy theory [18] and the life cycle methodology [19]. ECEC emphasizes the common basis of all human activities, *i.e.*, the consumption of solar-equivalent Joule (seJ), which has been extensively discussed by macro-ecosystem modelling in System Ecology [18,20,21]. According to the research from Yang et al. [22], diverse factors such as resource depletion, economic investment, and environmental impacts could be aggregated into one physical quantity, *i.e.*, ECEC, so that no arbitrary weighting is needed. Thus, ECEC could be a measurement of the overall ecological burden for informing policy and decision-making on sustainability.

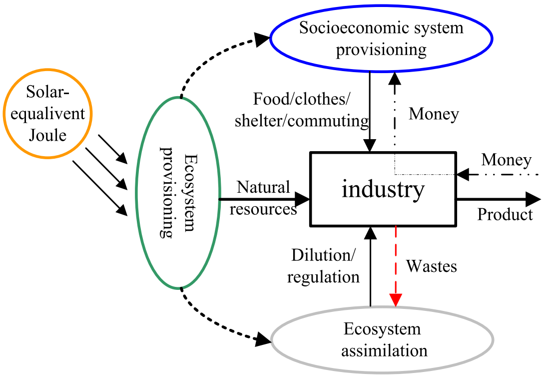

Fig. 1. The resource, economic and environmental factors of industrial processes [22].

The discussion above motivated the idea of sustainability assessment of BTL and CTL in the following. The life cycle inventories and economic costing are utilized to conpare among BTL, CTL, and conventional petroleum. Then ECEC analysis is used to compare the strengths and weaknesses of each alternative for accomplishing the integrated assessments. Further, the sensitivity analysis of coal prices, biomass transport distances, taxes, and transformities will also be discussed. Although the uncertainty might require further investigation, this research presents an initial and essential step to apply the ECEC method to process industry assessments.

2. Methodology and data

2.1. Life cycle boundary and models

The investigated BTL system converts biomass from the leftover straws, as mentioned in Section 1, to the transportation liquid fuels with a yield of 0.2 million tonnes annually. Since crops planting aims to produce food and the resultant straws are currently regarded as a source of pollutants which need treatment, none of the consumptions in the planting phase are allocated to such BTL. However, the carbon uptake credit of biomass (1.46 t CO_2/t) was considered [6,7]. Collected straws were assumed to be transported 50 km to BTL facility by truck. On the other hand, the CTL system converts bitumite to transportation liquid fuels with a yield of 1 million tonnes annually, and the transportation of bitumite was assumed the same as the national average of coal transportation pointed out by Liu et al. [23]. The property and ultimate analysis of straw and bitumite are presented in Table S1 in Supplementary Material.

The BTL and the CTL processes share a similar flow diagram including the feedstock pretreatment, gasification, water gas shift, acid gas removal, Fischer-Tropsch synthesis, distillation and hydrocracking. Detailed descriptions of these processes are presented in Fig. S1 in Supplementary Material. LPG by-product is used for heat and power generation. The finished fuel products include 27 wt% gasoline and 73 wt% diesel [24]. All of them were assumed to be transported 50 km to filling station by truck, then pumped into vehicles and ultimately burned for engine operation. As for conventional oil refinery, a national average model was taken from the Chinese Life Cycle Database developed by Liu et al. [23].

2.2. Economic analysis

The Total Project Investment (TPI) of BTL facility with a yield of 0.1 million tonnes/year was reported as about 2 billion CNY [25], while that at a yield of 0.6 million tonnes/year was 9.5 billion CNY [26]. It was assumed that TPI was approximately 125% [27] of the Fixed Capital Investment (FCI). Hence, the FCI of BTL facility with a yield of 0.1 million tonnes/year was about 1.6 billion CNY, while that at a yield of 0.6 million tonnes/year was 7.6 billion CNY.

Then, the FCI of BTL facility with a yield of 0.2 million tonnes/year was estimated by scaling base [28] from references as Eq. (1) that led to a FCI of 2.9 billion CNY.

$$FCI_{new} = FCI_{base} \times \left(\frac{Capacity_{new}}{Capacity_{base}} \right)^{Scaling\ factor} \quad (1)$$

The TPI of CTL facility with a yield of 1 million tonnes/year was reported as 12 billion CNY [29], and its FCI was assumed as 9.6