ACS Sustainable Chemistry & Engineering
Research Article
pubs.acs.org/journal/ascecg

Sustainability Assessment of the Coal/Biomass to Fischer−Tropsch Fuel Processes

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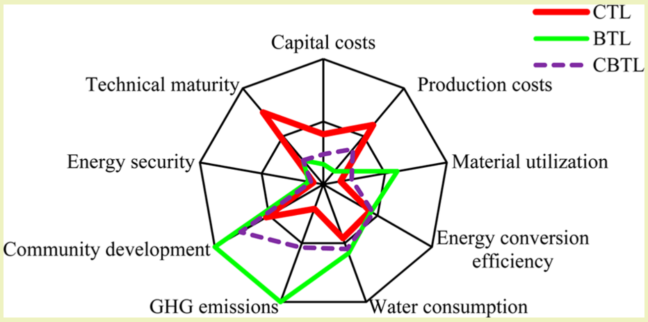

ABSTRACT: In recent years, developing alternative liquid to fossil fuels has drawn much attention from world industry. In China, the coal/biomass-based Fischer−Tropsch (FT) liquid is a promising alternative to address the shortage of petroleum supplies. However, there is a lack of systematic and quantitative assessment of sustainability of these processes. This paper proposes a multi-dimensional set of metrics to assess sustainability performance of the coal/biomass to FT liquids processes in China. The assessment indicates that the coal-to-FT fuel process performs well in technical and economic aspects, while unsatisfactorily in relation to environmental features. Besides, the production potential of coal-to-FT in China by 2020 is rather limited. On the other hand, the biomass-to-FT fuel process shows great potential for replacement of petroleum-derived fuels and good environmental performance, although it does not perform well in terms of economic and technical characteristics at present. Co-processing biomass with coal to make FT fuel is a preferable compromise option for its low GHG emissions and good economic performance, although further investigations and technical improvements are needed.

KEYWORDS: *Fischer−Tropsch synthesis, Coal-to-liquid, Biomass-to-liquid, Sustainability assessment, Metrics*

■ INTRODUCTION

The structure of energy sources in China is characterized as "deficient in oil, lean in gas, while rich in coal". With the rapid development of China's economy, oil consumption skyrocketed in recent years, up to 492 million tonnes in 2012, of which 278 million tonnes were imported.[1] The prospects of high oil price, petroleum depletion, and energy security have catalyzed interest in using alternative resources such as coal, natural gas, and biomass for replacement of oil.

Bioethanol, biodiesel, methanol, dimethyl ether (DME), and Fischer−Tropsch liquid (FTL) have attracted much attention as the alternatives to petroleum-derived transportation fuels. Among them, FTL derived from coal and biomass emerged as a promising alternative due to the following reasons: (1) FTL can be directly used to replace petroleum fuel, while no significant changes would be needed in infrastructure for fuel transportation. (2) FTL has high quality, with respect to sulfur and nitrogen contents, low aromatic content, and lower emissions of HC, CO, NO_X, and PM when compared to conventional fuels. (3) It can accommodate the wide range of feedstock. For example, coal, natural gas, or biomass can be converted to syngas from which FTL is synthesized. They are called coal-to-liquid fuels (CTL), gas-to-liquid fuels (GTL), or biomass-to-liquid fuels (BTL). Moreover, coal and biomass can be co-processed to produce FTL in a process called coal-and-biomass-to-liquid fuels (CBTL). The abundance and relatively low price of coal in China creates an opportunity to make FTL using coal. However, the production in China of natural gas-based FTL does not seem to be an attractive option due to the scarcity of natural gas reserves. Biomass as a renewable resource with a hydrocarbon structure has long been a focus of efforts intended at making liquid fuel. Therefore, the main focus of this paper is FT liquid fuels obtained from coal and biomass in CTL, BTL, and CBTL processes. Many previous studies have been devoted to evaluation of technical and economic aspects of processes[2−4] for production of synthetic liquid fuel. However, relatively modest effort was made to analyze the social and environmental impact of those processes, despite the fact that both aspects are very important when evaluating the sustainability of large-scale industrial implementation.[5,6]

Sustainability analysis and evaluation of the chemical and energy aspects of the process can provide important hints for their improvement. Moreover, they can offer guidance for design of new processes, reduction of waste release, and consumption of material and energy resources.[7] The previous research aimed at application of the different methodologies to capture sustainability of the chemical and energy processes, including exergy,[8] eco-efficiency analysis,[9] and life cycle

Special Issue: Sustainable Chemical Product and Process Engineering

Received: September 4, 2013
Revised: November 14, 2013
Published: November 15, 2013

assessment,[10] as well as sustainability indicators.[11] The aggregated indicators enable analysis of complex information and facilitate decision making aimed at achieving process sustainability. This approach has been applied to evaluate the sustainability of wastewater treatment systems,[12,13] land utilization,[14,15] regional development,[16] and chemical and energy processes.[17]

This paper aims at evaluation of the sustainability performance of coal/biomass to FTL processes. It is achieved by use of multi-dimensional sustainability indicators for capturing technical, economic, social, and environmental aspects of the analyzed processes. The analyzed results are compared with the traditional petroleum refinery process.

METHODOLOGY FOR SUSTAINABILITY ASSESSMENT

The use of sustainability indicators for evaluation of process performance aims at providing holistic and integrated assessment enabling identification of advantages and drawbacks of the analyzed processes. There are four steps to be considered when applying the indicator-based sustainability assessment: (1) indicator identification, (2) data processing, (3) weighting of indicators, and (4) their aggregation.[18] The above-mentioned issues were studied by many researchers.[11,14,19−21] GREENSCOPE subtly chose a series of reference point for each indicator.[14] Dinh et al. applied an analytic hierarchy process in weighting among indictors.[20]

FTL processes are characterized by the complex internal flows of mass and energy, as well as very complicated environmental, social, and economic interactions with the neighboring systems. In reference to a number indicator sets proposed in the literature,[9,11,14,20,22]a multi-dimensional set of sustainability indicators is identified in this work to assess the sustainability of coal/biomass to FTL processes. The above-mentioned indicators and corresponding subindicators are presented in Table 1.

Table 1. Indicators for Sustainability Assessment of CTL, BTL, and CBTL Processes

			reference value	
indicator	subindicator	unit	best	worst
Economic				
I_1 investment	10^3 \$/(tonne/y)	0	3.4[23]	
I_2 production cost		\$/barrel	0	147[24]
Environmental				
I_3 material utilization	material efficiency efficiency	%	100	0
	renewability	%	100	0
I_4 energy efficiency	%	100	0	
I_5 water consumption		t/t	0	22[25]
I_6 GHG emissions	$kgCO_{2eq}/GJ$	0	259[23]	
Social				
I_7 community	employment	staff/10^3tonnes	30.3[27]	0
I_8 energy security		%	100	0
Technical				
I_9 technical maturity		--	1	0

Economic Indicators. Costs minimization and maximization of profits are very often used as the optimization criteria when designing/operating industrial processes. The proposed economic indicators for coal/biomass-to-FTL processes are given as follows.

Investment Cost. The average capital investment for unit capacity is adopted for the comparison of different alternative processes for making liquid fuels, as the production scale of alternatives are always different. The metric used is thousand dollar per unit output of liquid fuel per year.

Production Cost. Production costs of FTL are represented as the price of crude oil (US\$/barrel) at which the wholesale price of petroleum-derived products would equal to the calculated costs for production of FT fuel on a GJ (giga joul) basis.[23] This is an important economic index and is easy to compare to the current price of crude oil.

Environmental Indicators. The production of liquid fuel requires consumption of raw material and energy, which leads to resource depletion. Simultaneously, the production and final consumption of liquid fuel release waste into the environment, which causes environmental degradation. Therefore, reduction of waste at the source and using resources more efficiently should be always the goals when optimizing chemical processes. The proposed environmental indicators cover the following aspects: material utilization (subindicators are renewability and material efficiency), energy conversion, water consumption, and greenhouse gas emissions.

Material Utilization. . There are two subindicators of material utilization: material efficiency and renewability. The former is calculated as the ratio of target product (FT fuel) yield and its main feedstock input, shown in eq 1. For the sake of simplicity, such main feedstock include only crude oil, coal, and biomass.

$$\text{Material efficiency} = \frac{\sum \text{mass of product}}{\sum \text{feedstock input}} \times 100\% \qquad (1)$$

The use of renewable resources, aimed at diminishing the consumption of fossil fuels, is a significant factor supporting sustainable development. Renewability is expressed as the mass ratio of feedstock from renewable resources to total main feedstock input as shown in eq 2.

$$\text{Renewability} = \frac{\sum \text{renewable feedstock input}}{\sum \text{feedstock input}} \times 100\% \qquad (2)$$

Energy Conversion. In coal/biomass to FT liquids processes, coal and biomass are not only used as raw materials but also as energy carriers. Essentially, the production of FT fuel from coal and biomass is to convert them into another energy form so that they could be easily utilized. Particularly for coal as a nonrenewable resource, the conversion makes sense only under high resource energy efficiency. The calculation of resource energy efficiency is expressed as eq 3.

$$\text{Energy efficiency} = \frac{\sum \text{calorific value of product}}{\sum \text{calorific value of input}} \times 100\% \qquad (3)$$

Water Consumption. Along with the increasing scarcity of water resources and growing awareness of environmental protection, the reduction of water consumption and improvement of its efficient use have become important optimization goals for chemical enterprises. Water consumption indicator is expressed as tonnes of fresh water consumed per unit FTL output as shown in eq 4.

$$\text{Water consumption} = \frac{\sum \text{mass of fresh water consumed}}{\sum \text{mass of output}} \times 100\% \tag{4}$$

Greenhouse Gas (GHG) Emissions. Global climate change, caused mainly by greenhouse gas emissions, has become one of the major challenges of environmental protection at the global scale. Energy and chemical processes have already become one of the key areas for greenhouse gas emissions mitigation in China.[24] The indicator includes CO_2 equivalents emitted from the production and consumption of 1GJ liquid fuels. Greenhouse gases, such as CH_4 and N_2O, are expressed as CO_2 equivalents in accordance with their warming effect and next summed up. The calculation is performed as follows.

$$\text{GHG emissions} = \frac{\sum \text{mass of } CO_2 \text{ equivalents emitted}}{\sum \text{energy content of output}} \times 100\% \tag{5}$$

Social Indicators. Social area is one of the fundamental elements of sustainability. The coal/biomass to FT liquids process can bring many social benefits, such as ensuring energy supply so thus national security, increasing local employment, promoting regional economic development, etc. The proposed social indicators are community development and energy security.

Community Development. This indicator is qualitative one, and it comprises many complicated phenomena. For simplicity, a subindicator of employment opportunities offered by the coal/biomass to FTL process is adopted to indicate community development, i.e., the job opportunities provided by investments in plants that will produce 1000 tonnes of liquid fuels per year.

Energy Security. The purpose of making FTL from coal and biomass is to partially replace petroleum-based fuels, diverse China's energy supply, and therefore enhance national security. The indicator is expressed as the ratio of expected capacity of FTL to the total oil demand. As for conventional oil refinery process, the indicator is presented as domestic supply ratio of oil. The higher this indicator is, the lower is the oil dependence on imports and the safer is energy security

Technical Indicators. The technical area has been commonly emphasized as a wider aspect of sustainability for energy and chemical process. It is generally used to characterize the ability of the process to achieve, maintain, and improve its performance of purposed functions, such as the indicator of system reliability, system operability, etc.[25] The indicator of technical maturity is referred to as the ability of he process to achieve its specific function. Only when the production technology of FT fuel from coal and biomass is mature and reliable can it be implemented and promoted at the commercial scale. Therefore, the proposed technical indicator is technical maturity.

Technical maturity is a qualitative indicator using the categorical scaling method to quantify the concept in the range 0−1, where 1 signifies the best case, i.e., the technology has achieved large-scale industrial operation; 0.75 represents a demonstration project or pilot stage; 0.5 denotes a small test phase; 0.25 indicates a laboratory research stage; and 0 represents the worst case, i.e., the relevant basic research has not yet started.

Reference Point for Indicators. After identifying sustainability indicators, a choice of reference point for each indicator will be quite helpful in the interpretation phase. The reference point for each indicator includes its best-case score and worst-case score.[26] Different reference states are chosen as the worst and best scenarios according to the criteria obtained from literature reviews or definition of indicators. The literature review of production processes of alternative fuels and subsequent comprehensive comparisons are carried out to determine boundary values for each indicator as shown in Table 1.

RESULTS AND DISCUSSION

An extensive literature survey has been conducted to collect data enabling verification of the proposed indicators and analyze the sustainability of coal/biomass-to-FT liquids processes, keeping in mind economic, environmental, social, and technical aspects. In this paper, the boundary of these three applications are confined to the production process, excluding raw material mining, preparation, and transportation stages. This is because this paper is written to justify the applicability of sustainable indicators to the processes with different feedstocks to the same product. More focus is therefore paid on the difference between the analysis with these multiple indicators together and the one with a single indicator. The detailed comparison and validation of data from the different literature sources is carried out in order to verify data accuracy and reliability.

Economic Sustainability. *Capital Costs.* The processes of coal/biomass-to-FT liquids are large scale and capital intensive. The total capital costs of the CTL industrial demonstration project with the capacity of 1.096 million tonnes liquid product/yr is up to 2.25 billion US$, i.e., 2055 US$/(tonne/y).[28] [This demonstration project was buildup in 2011 in Yulin, China, by Yankuang Energy R&D Co., Ltd.] However, BTL processes are much more expensive. The capital cost of the BTL process with a capacity of 4409 barrel liquid product/day (0.22 million tonnes/yr) is 640 million US$, i.e. 2800 US $/(tonnes/y). According to a report on CBTL process with 36,700 barrels product/day and 38% mass fraction of biomass in feedstock,[23] the unit investment cost of CBTL project is 2603 US$/ (tonnes liquid product/yr). The above costs are presented from Chinese currency using the average mid-2007 exchange rate of US$ to RMB, i.e., 7.3. The capital costs of a conventional refinery in China with a crude oil processing capacity of 10 million tonnes/yr is about 2.38 billion US$,[29] i.e., 315 US$/ (tonnes liquid product/yr), where the light oil yield is considered as 74%.[30] Figure 1 shows the capital costs for the coal/biomass-FT liquids and oil refining processes. The capital costs of BTL processes are approximately 10% greater than

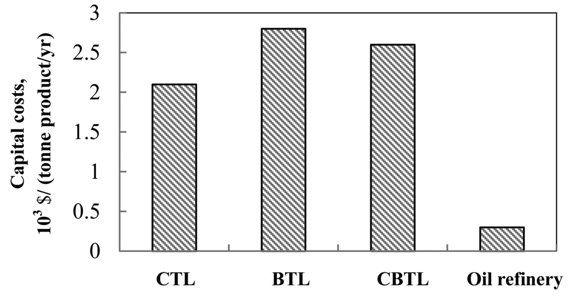

Figure 1. Comparison of the capital costs of CTL, BTL, CTBL, and the oil refining processes.

those for CBTL, 40% higher than those for CTL, and 8 times greater than those of the oil refinery process.

The coal/biomass-to-FT liquids processes make a great impact on a country's economy. The larger the scale of production is, the less the capital cost and the higher the energy and material efficiency of the process. A considerable economic benefit could be realized when the production capacity for the CTL process is greater than 1 million tonnes/yr and that of BTL is 0.8−1.59 million tonnes/yr.[28,31] However, one has to remember that biomass has a low energy density, and it is estimated that biomass productivity is around 1.5 kg/square meters. In consequence, it is necessary to dedicate large areas of land in order to satisfy the demand for raw material. Moreover, logistics related to collection and transportation of biomass is rather complicated due to the seasonal supply of biomass. The production capacity of an existing BTL facility in China is less than 0.8 million tonnes/yr.[32] The CBTL process inherits the scale advantage of the CTL process, so it suffers less from this limitation compared to BTL.

Production Costs. The production cost of FT liquids is closely related to the price of raw material, investment costs, process selection, and process optimization.[28] When the discount rate is taken as 6%, then the cost of the coal-based FT liquids is about 411 US$/tonne, which corresponds to the costs of producing liquid fuels from crude oil when the price of crude oil is 50 US$/barrel.[28] The production cost of FT liquids from biomass only and hybrid biomass and coal are equivalent to 127 and 93 US$/barrel of crude oil, respectively, as the coal price is $1.7\ \$/\mathrm{GJ}_{\mathrm{HHV}}$ (i.e., 39 US$/tonne) and biomass price is 5 US$/GJHHV (i.e., 93.3 US$/tonne).[23] The price of crude oil has rocketed in recent years from 72 US$/barrel in 2007 to 111.3 US$/barrel in 2011 (Brent crude oil price).[24] That is an increase of 54%. It can be concluded that the production cost of the FT liquids from coal is lower than that of petroleum-based fuels, while that of FT liquids from biomass is 76% higher than that of petroleum-based fuels. However, if the carbon reduction policy is to be implemented, BTL and CBTL with low CO_2 emissions will present many more economic advantages.

Environmental Sustainability. *Material Efficiency.* As to the CTL process, it is reported that about 3.6 tonnes of raw coal is consumed for 1 tonne of fuel (taking the average of 3.5 tonnes in ref 33 and 3.7 tonnes in ref 28), i.e., the material efficiency is about 28%. [This is according to a CTL facility buildup in 2008 in Erdos, China, by Yitai Co., Ltd. This facility yields about 160,000 tonnes liquid product per year.] About 5 tonnes of biomass is needed to make 1 tonne of FT fuel,[31] i.e., the material efficiency of the BTL process is around 20%. The material efficiency of CBTL is affected by the feedstock composition. When biomass occupies 43% in raw material inputs (based on high calorific value), the process requires 4.4 tonnes of feedstock for 1 tonne of fuels. In this case, the material efficiency is 23%. In term of oil refining process, the material efficiency is about 74%.[30] The comparison of material efficiency of FT based on oil refining and processes using alternative resources is shown in Figure 2. It is shown that the material efficiency of the oil refinery process is generally 1.6−2.7 times higher than that of alternative processes. The material efficiency of the CTL process is 40% higher than that of BTL. China possesses rich coal reserves. However, the reserve−production ratio of the proved coal reserves is only 33, and it is far below the world average of 112.[24] Simultaneously, it is estimated that in China[34] there is annually available around 460 million tce (tonnes of coal equivalent) biomass for energy conversion. Therefore, there is a large potential for developing biomass-based chemical routes, especially in FT processes.

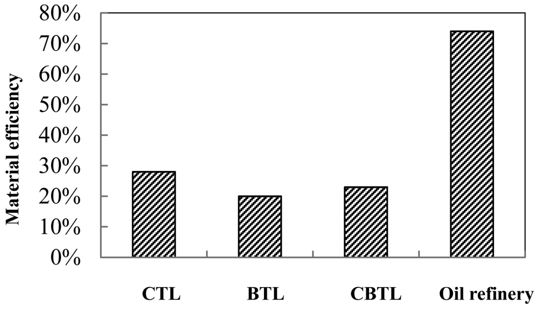

Figure 2. Material efficiency of CTL, BTL, CBTL, and the oil refining processes.

Renewability. The renewabilities of CTL- and petroleum-based fuels are 0, while that of BTL is 100% ,and for CBTL, it is determined by the proportion of the biomass in feedstock. The value of the indicator is growing with an increase in biomass ration in the feedstock, e.g., when biomass is accounted for 0.56 in mass fraction, the renewability of CBTL is 56%.

Energy efficiency. The BTL process has higher energy efficiency, equal to around 46.2%,[28] than those of the CTL and CBTL processes. Their values are 43.3% and 44.2%, respectively.[23] Energy efficiency of the oil refinery process is calculated as 75%, assuming the average light oil yield of 74% in China and the heat value of crude oil and oil product are 42MJ/kg and 42.5 MJ/kg, respectively. It is 63−74% higher than for the coal/biomass-to-FTL processes.

Water Consumption. There are two major sinks for water consumption in FT processes using the alternative resources. One is the gasification and gas shift process, and the other is process utility in heat transfer and in the cogeneration of electric power.[23,35] The CTL process is water-intensive, and fresh water usage is up to 12 tonnes per tonne of FT liquids.[33] The consumption could be reduced to 8 tonnes due to water-saving modifications of the process (e.g., sewage treatment recycling). If biomass content is 39% in the feedstock, then the water consumption in the CBTL process is 10% lower than that for the CTL process.[36] It is estimated that water consumptions in the BTL and CBTL processes are 10.8 and 10 tonnes per tonne of FT liquids, respectively. The water consumption in oil refining is about 1.4 tonnes per tonne of product. This means 8.5 and 6.1 times lower than those in the CTL and the BTL processes.

Greenhouse Gas Emissions. Greenhouse gas emissions associated with the production and use of coal-based FT liquid are approximately 205 kg CO_2-equivalent per GJ HHV liquid fuels. This means about 2.0−2.2 times more than that for petroleum-based oils.[23] CO_2 emissions increase with a decreasing H/C ratio of raw materials. Coal has a much lower H/C ratio than crude oil, being 0.2−1.0 and 1.6−2.0, respectively. In contrast, total-fuel-cycle GHG emissions of BTL are approximately zero. This is due to the fact that all carbon in biomass is originally derived from CO_2 in the atmosphere, except for a small amount of conventional fuel consumed in production and transportation. A simple method for diminishing CO_2 emissions is to add H_2 to the CTL process. Therefore, integrating biomass into the CTL process is an appropriate method for mitigating CO_2 emissions. When the proportion of biomass in feedstock is 43%, then production and use of FT liquids result in 120 kg/GJ total-fuel-cycle GHG emissions. This is almost the same amount as that for the petroleum-based oils.[23]

Another major CO_2 reduction method, besides the co-feeding process with the hydrogen-rich feedstock, is to apply carbon capture and storage technology (CCS). A successful CCS application has been established by the Shenhua group in China, with a reduction capacity of 100,000 tonnes CO_2/yr.[37]

Social Sustainability. *Community Development.* The majority of coal-rich areas is situated in northwestern China: Inner Mongolia, Shaanxi, and Ningxia provinces. Therefore, the development of a coal industry can strongly support regional economic development and as a result can increase employment in the region.[38] On the other hand, the development of a biomass-based energy-generating industry can facilitate reuse of agroforestry residues. This could have a significant impact on the restructuring of agriculture and development of the local rural economy. It is estimated that in China the marginal land area for biomass cultivation is 1,640,000 km^2.[39] For every investment of 1000 tonnes of product, a CTL plant will create about 16 jobs,[40] while a BTL plant will provide 30.3 (assuming the job opportunities provided by BTL are the same as the bioethanol industry, which is also a biomass-based energy-generating industry).[27] The average number of jobs provided by CTL and BTL plants is set to the employment opportunities created by CBTL. For comparison, at the same time, an oil refinery would create about five jobs.[41]

Energy Security. With quick economic development in recent years, China consumes more and more oil. It is predicted that China's oil demand will be 450−610 million tonnes in 2020.[42] The production capacity of the CTL industry is expected to reach about 50 million toe (tonnes of oil equivalent) in 2020.[28,43] Assuming China's oil demand in 2020 as 610 million tonnes, coal-based FT liquid could satisfy 8% of the total oil demand. The production capacity of the BTL industry is estimated to be 73 million toe in 2020, assuming that the capacity grows linearly from 35 million toe in 2015[33] to 150 million toe in 2030.[44] This could satisfy 12% of the total oil demand. In fact, a key official who works in the Chinese Academy of Forestry made a forcast that China will have a maximum 321 million toe biomass feedstock for oil production. For CBTL, energy security is taken as the average value of CTL and BTL, i.e., 10%. For a conventional oil refinery industry, the energy security will be 33% in 2020, assuming the same crude oil production capacity as current, i.e., 200 million tonnes per year until 2020. The biomass could be an important alternative for oil. However, a conventional oil refinery would still dominate fuel production for a long period of time.

Technical Sustainability. The SASOL Company first industrialized the coal-to-FT liquids process in South Africa in the early 20th century.[38] The Institute of Shanxi Coal Chemistry, Chinese Academy of Sciences, started the research and development of CTL technology in 1980s. The developed CTL technology (iron-based catalyst and slurry bed FT reactor) has succeeded in the demonstration projects built by three large companies: Yitai, Luan, and Shenhua group.[28,33] The BTL technology is until now applied in small-scale demonstration installations. CHOREN Company launched the first BTL industrial demonstration project with a capacity of 15,000 toes/yr in Germany in 2007, using the ChorenCarbo-V process.[31] According to China's bioenergy strategy, several BTL and polygeneration demonstration projects will be launched by the end of 2015.[33] The CBTL technology is currently in a developing stage. The United States plans to build 3−5 CBTL demonstration plants in 2013−2016.[45] However; there has not been any demonstration project in China.

The technical maturity of CTL, BTL, CBTL, and the oil refinery technologies is 0.75, 0.25, 0.25 and 1, respectively. Currently, the active research in FT liquid focuses on gasification, catalyst selection, and reactor design of FT synthesis and CO_2 capture and storage, as well as a scale-up of the process.

Overall Sustainability. The results of the above indicators are shown in Table 2. It should be noted that the boundary of these three applications are confined to the production process, excluding the raw material mining, preparation, and transportation stages. This is because this paper is written to justify the applicability of sustainable indicators to the processes with different feedstocks to the same product. More focus is therefore paid on the difference between the analysis with these multiple indicators together and the one with a single indicator. The issue of a systematic comparison is out of the scope of this paper, and it will be handled in a future publication. For the option with both coal and biomass as feedstock, the fraction of biomass in feedstock mentioned in this paper ranges from 38% to 56%. This is due to data availability. On the other hand, a realistic CBTL process actually does not run at a fixed ratio of coal-to-biomass because of the seasonal supply of biomass. An appropriate range of coal-to-biomass ratio in a CBTL process is acceptable.

Table 2. Comparison of Indicators for CTL, BTL, CBTL and Conventional Refining Processes

indicator (subindicator)	CTL	BTL	CBTL	Oil refinery
Economic[a]				
capital costs (thousands \$/(tonne/y))	2.1	2.8	2.6	0.3
production costs (\$/barrel)	50	127	93	72
Environmental				
material efficiency (%)	28	20	23	74
renewability (%)	0	100	56[b]	0
water consumption (t/t)	11.9	10	10.8	1.4
energy efficiency (%)	43.3	44.2	46.2	75
GHG emissions ($kgCO_{2,\ eq}$/GJ)	205	0	120	94
Social				
employment (staff/1000 t)	16	30	23	5
energy security (%)	8	12	10	33
Technical				
technical maturity	0.75	0.25	0.25	1

[a] Costs are expressed in constant mid-2007 U.S. dollars, and the exchange rate of RMB to USD is 7.3. [b] Biomass is accounted for 43% in feedstock inputs (based on its high calorific value).

It is shown in Table 2 that the capital costs of the CTL and BTL processes are extremely high. This means 6.5−9.1 times over the oil refinery process. The production costs of the CTL process is 22% lower than that of the oil refinery process. The production costs of the BTL process is the highest. It is 2.5 times higher than that for oil refinery process. In terms of environmental performance, the BTL process has the best material efficiency. The CTL process suffers from the largest water consumption, being 2.3 times higher than the oil refinery process. The CTL, BTL, and CBTL processes have similar energy efficiency, which is much lower than that of the oil refinery process. Total-fuel-cycle GHG emissions of the CTL process is 2.2 times higher than that of petroleum-based oils, while the BTL process release causes almost zero emissions. When evaluating the social aspects, the BTL industry provides 2 times more jobs than that of the CTL industry. The capability of the BTL industry to satisfy the oil demand in China is about 1.5 times that of the CTL industry. The CTL technology is relatively mature and reliable, while the BTL and CBTL technologies are still under development without any large-scale industrial installations.

To interpret and compare the overall sustainability of different alternatives, a further processing of these indicators is necessary. For normalization purposes, the indicator is expressed as the relative difference between the actual and worst case, as presented in eq 6

$$X_{ij} = \frac{x_{ij} - \text{worst}\{x_j\}}{\text{best}\{x_j\} - \text{worst}\{x_j\}} \tag{6}$$

where x_{ij} is the indicator j for process i; best$\{x_j\}$ is the assumed best case of indicator j; worst$\{x_j\}$ is the assumed worst case of indicator j; X_{ij} is the normalized indicator j for process i. The indicator varies in the range [0,1]. The greater the index value is, the better its sustainability is. The best and worst cases of indicators are shown in Table 1.

There are two subindicators of the indicator of material utilization. The value of the material utilization is calculated as an average of two subindicators (assuming that both of them have the same weight). The value of the indicator in Table 2 is calculated by using eq 6. The results are also shown in a graphical manner in Figures 3−5.

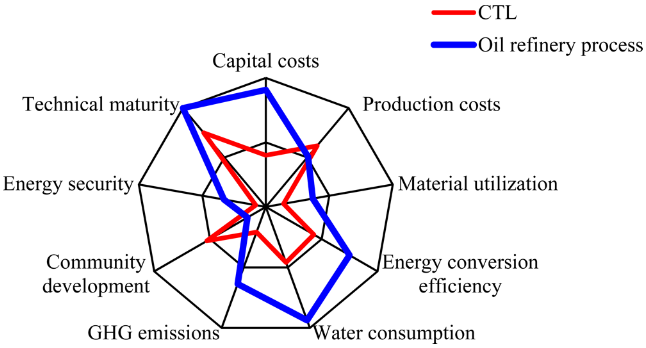

Figure 3. Sustainability assessment and comparison of CTL and petroleum refinery processes.

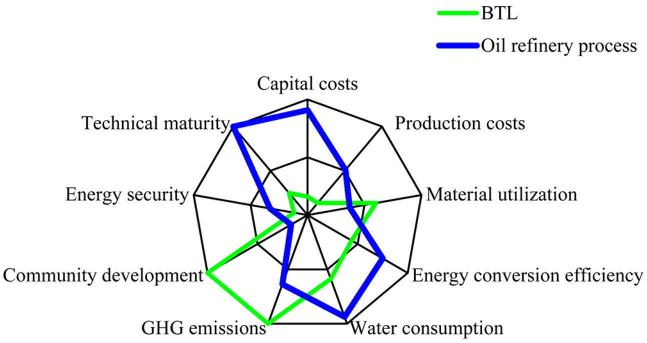

Figure 4. Sustainability assessment and comparison of BTL and petroleum refinery processes.

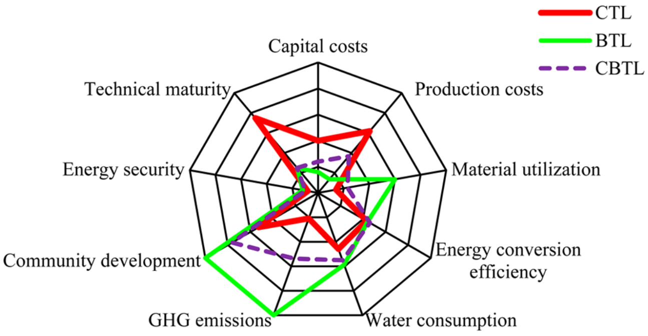

Figure 5. Sustainability assessment of CTL, BTL, and CBTL processes.

The CTL process has relatively low production costs, as shown in Figure 3. It facilitates the development of the CTL process, although its capital cost is much higher than that of the petroleum refinery process. In the environmental aspect, the poor performances of the CTL process greatly undermine its overall sustainability. The GHG emissions and water consumption in the CTL process are much larger than those for the traditional route, and simultaneously its material and energy efficiency is low. The development of the CTL process could provide more jobs and hence promote community development. However, its potential to replace petroleum-based fuels is rather limited, despite its technical maturity.

The BTL process does not offer a good economic performance because of its high capital and production costs, as shown in Figure 4. Moreover, its technical feasibility still needs to be improved in the process of long-term development.

The BTL process is relatively environmentally friendly due to low GHG emissions and high material utilization. However, the high water consumption might still be its weakness. The BTL process could ensure a large number of jobs. It also possesses great potential for replacing the conventional refinery processes.

Simultaneous use of biomass and coal to produce FT liquids emits less GHG and brings more economic benefit in comparison to the CTL and BTL processes (Figure 5). However, it has some drawbacks, e.g., high consumption of water, low energy efficiency, and high capital costs. Moreover, this complex technology is still immature and requires further studies.

Finally, the conventional refinery process is still cost effective when compared to the alternative processes due to lower capital cost and water consumption, as well as higher energy efficiency and technical maturity. However, it offers less jobs and is very sensitive to the variations in oil prices.

■ CONCLUDING REMARKS

The CTL/BTL/CBTL processes are especially important for China as the country is facing a severe shortage of oil resources. This paper applies the concept of sustainability for evaluation of those processes. It allows us to assess CTL/BTL/CBTL processes from economic, environmental, social, and technical perspectives.

It was found that the CTL process is required for low production cost, but it emits more GHGs when compared to the conventional oil refinery process. The major objective of developing the CTL process is to decrease the consumption of oil in China. However, for sustainable development of CTL, the additional technologies for reduction of emissions, such as carbon capture and storage, should be applied. The BTL technology is still immature, and its economic feasibility in China has not been yet proven. However, it is superior to the

CTL and refinery processes with respect to environmental performance. In addition, with the large reserve of biomass in China, BTL processes have a large potential for replacing refinery processes. The CBTL process combines the advantages of the CTL and BTL processes. It is a preferable compromise option for its low GHG emissions and good economic performance. However, this complex technology is still immature, and further study and development is required.

To adapt to the high competition of oil throughout the world, it would be the best choice for China to diversify the conventional refining industry with alternatives like CTL/BTL/CBTL. By including emissions reduction techniques in the CTL process, while improving the techniques for the BTL and co-feed processes, these alternative processes could greatly facilitate the sustainable development of the energy supply in China.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors are grateful for financial support from the China NSF key project (No. 21136003), China NSF project (No. 21306056), and National Basic Research Program (No. 2012CB720504 and No. 2014CB744306).

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