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Technology portfolio of China liquid fuel industry to address energy security and environmentally friendly development

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Abstract

Efforts to secure alternative technologies for producing liquid fuel from biomass, oil shale, and coal have been intensified in recent year. Different levels of dependence on oil imports and carbon prices have a great impact on the development of new technologies. How should China configure its liquid fuel industry in the future considering these factors? This paper proposes a model to optimize the technology portfolio and capacity configuration of these technologies by minimizing their total accumulated cost from 2015 to 2045. With different scenarios for carbon prices and the level of dependence on oil imports, we find that oil refining will remain dominant in China's liquid fuel industry over the next three decades, and the coal to liquid fuel (CTL) process will be competitive in low carbon price; otherwise, biomass to liquid fuel (BTL) will be more competitive than CTL. When decreasing the level of dependence on oil imports, biomass to liquid fuel (BTL) and CTL can be established as technology stocks for energy safety, but the share of BTL and CTL adoption does not continue to monotonically increase. Further implies that reducing the level of dependence on oil imports might also be a good decision for reducing the system total cost, since it could might result in more adoption of renewable resources and clean technology.

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Introduction

Since China's economic strength started rapidly improving and people's living standards improved, the liquid fuel (diesel and gasoline) consumption of China has increased dramatically. China is an oil import country, and thus, it must import a large amount of crude oil from overseas to satisfy its ever-increasing demand. In 2018, China imported more than 461 million tons of crude oil, which accounted for 72% of its total crude oil consumption (Nation Bureau of Statistics). However, the long-term trend is toward a crude oil shortage, and this increased dependency on a relatively limited number of oil-producing countries holds serious risks for energy security and global social stability. Higher oil import dependency means lower energy security (Kong et al., 2019). One feasible method for alleviating the high risks to oil supply caused by high oil import dependency is to seek alternative sources for liquid fuel production. In this avenue, biomass to liquid fuel (BTL), oil shale to liquid fuel (STL), and coal to liquid fuel (CTL) can play prominent roles in China's energy sector. Speeding up the development and utilization of alternative resources and technologies as liquid fuel sources will improve the diversity of China's energy structure.

China's proven energy reserves are characterized by rich coal but scarce oil (Xie et al., 2010), and coal will play a pivotal role in China's energy economy in the coming decades (Wang et al., 2011). Developing CTL technology has attracted increasing concentration in China, as it can derive fuels from coal to replace and supplement conventional supplies of diesel oil and gasoline from crude oil (Mantripragada and Rubin, 2013). To address aspects of energy security and future sustainable development, a series of policies have been established to accelerate the exploitation of unconventional oil resources, such as oil from oil shale pyrolysis and shale. As a promising alternative feedstock, the reserve of oil shale is $7.2*10^5$ Mt, and the recoverable amount of shale oil pyrolyzed from oil shale in China is 4.76 Mt, which is twice China's crude oil reserves (Yang et al., 2016). The abovementioned resources are both nonrenewable energy sources, and processes for converting these sources to liquid fuel are characterized by high energy input and large amounts of greenhouse gases (Zhou et al., 2016). Biomass is a renewable and carbon-neutral energy source, and the chemical utilization of biomass for producing liquid fuel is also a sensible method. Using nonfood biomass, including forestry and agricultural residues, would not vitally increase food prices or lead to net CO_2 emissions (Fargione et al., 2008). By 2015, the liquid fuel production capacity from CTL, STL, and BTL in China had reached 4.3 Mt, 1.4 Mt, and 0.68 Mt, respectively (National Energy Administration of China, 2017), and the predicted total capacity of CTL plants, STL plants, and BTL plants will reach 20 Mt/y (Wang, 2014), 3 Mt/y (Gen et al., 2013), and 2 Mt/y (KAIDI Group Co., Ltd., 2013) by 2030. From the above discussion, the liquid fuels produced in China from biomass, oil shale, and coal appear promising.

To date, the analysis of OR, BTL, STL, and CTL technologies has mainly concentrated on estimating capital costs or on technoeconomic assessments of their production plants (Swanson et al., 2010; Mohajeran et al., 2018; Zhou et al., 2019). Swanson et al. (2010) used a comprehensive comparison between the capital and production costs of two biomass-to-liquid production plants; Qin et al. (2018) conducted a technoeconomic analysis of the CTL process with different entrained flow gasifiers; Yang et al. (2020) compared STL and oil refining, focusing on technical, economic, and environmental analyses. Historical studies involving technoeconomic analyses provide some suggestions for China as to what kind of liquid fuel production technologies should be taken into account; however, they pay little attention to aspects of how China should configure different liquid fuel production technologies in the coming decades, and few studies exploring these questions can be found in the existing literature. To address this knowledge gap, the overall objective of this research is to advance methods for science-based decision-making support to address key problems in optimizing the technology portfolio of China's liquid fuel industry from a long-term perspective.

In addition, it is important to note that the technology portfolio in the liquid fuel industry will be affected by many factors, such as carbon prices, feedstock prices, technological learning, technology localization, energy security (Mantripragada and Rubin, 2013; Xiang et al., 2014). Currently, much of the work analyzing feedstock prices and technological learning exerts a strong influence on the development of liquid fuel technologies. For example, Xu et al. (2020a) showed that oil and coal prices play important roles in the total production cost of olefins; beyond their role, technological learning and energy efficiency will also influence the technology portfolio in China's olefin industry (Xu et al., 2020b). Empirical studies have shown that carbon price and oil import dependency also play important roles in the adaptation of emerging technologies. Carbon price is an efficient policy that can address the externalities of energy use (Best, 2020). Many case studies of individual countries show substantial impacts of carbon-pricing schemes, such as carbon pricing leading to the transition from coal to renewable energy (Murray and Maniloff, 2015; Bakhtiari, 2018; Best and Burke, 2018). Energy security has also become a focal topic from the political and scientific perspectives (Chen et al., 2018), and oil import dependency is an important factor in assessing energy security. For example, Berndes and Hansson (2007) studied the prospects for using domestic biomass resources under different policy objectives (cost-effective climate change mitigation, employment creation, and reduced imported fuels dependency); Kong et al. (2019) used system dynamics models to predict the development of China's CTL industry when considering energy security, economic, and environmental qualifications. However, existing models seldom provide a comprehensive analysis of the composition of different liquid fuel technologies when considering both energy security and dynamic carbon price.

Unlike previous research, this study proposes a method for exploring the technology portfolio of China's liquid-fuels industry using a simplified optimization system model under different scenarios. The model minimizes the accumulated total costs of China's liquid fuel industry from 2015 to 2045 with a time step of 1 year to meet the given liquid fuel demand. Cost minimization is only the surrogate goal for this model, but it is subjected to a series of qualifications, e.g., oil import dependency, capacity limitations, and demand constraints in which the demand is exogenous. This research will offer implications for decision-makers to help them develop better policies for promoting the development of the liquid fuel industry.

The remainder of this paper is organized as follows. Section 2 introduces the technologies selected in this research. Section 3 presents system optimization models of technology adoption with energy security and carbon price. Section 4 discusses the initialization of parameters. Section 5 introduces the carbon price and oil import dependency scenarios, and we then analyze the results under the four scenarios. Section 6 gives concluding remarks and policy implications.

Technological options

The current energy structure of China is ample domestic coal, sufficient oil shale, available biomass and scarce crude oil, which means that the liquid fuels produced in China from oil shale, biomass and coal are likely to increase. Otherwise, China's oil refining industry is the second largest in the world and provides products to many sectors. This is the main reason that we choose these four raw materials and technologies.

Oil refining was developed more than a century ago, and its capacities increased quickly, resulting in a well-established technology with unquestioned economic dominance. However, high oil prices and continuing concern about energy security have shifted attention to alternative energy supply technologies (Liu et al., 2013). Coal holds a large share in China's energy mix, so efficiently developing a new coal chemical industry is of interest to China. Direct and indirect coal liquefaction are two basic approaches with the potential to produce liquid fuels from coal (Jiang and Bhattacharyya, 2015). Both direct and indirect CTL methods have been commercialized in China for decades (Tennant, 2014). In general, CTL is a process that derives products from coal to replace and supplement conventional supplies of diesel oil and gasoline derived from crude oil (Mantripragada and Rubin, 2013).

For energy security and to decrease oil import dependency, China's government has implemented a series of policies to encourage the exploration and utilization of unconventional oil-gas resources, such as oil shale (NEA, 2016). Biomass, as a renewable resource, emits fewer carbon emissions during its conversion to liquid fuels in BTL (biomass-to-liquid) processes and thus has attracted more attention. The first renewable fuel technologies were biomass to diesel and ethanol derived from corn (Swanson et al., 2010). The greatest disadvantage in the commercialization of the BTL industry is its lack of economic competitiveness in the energy market, especially due to its high capital costs, so this process has developed slowly.

Currently, the volume of liquid fuels produced in China from oil shale, coal, and biomass is likely to increase. Most of the economic analyses of these technologies focus on cost-benefits, so with the decrease in oil prices in recent years, it has become unprofitable to develop these technologies. However, proponents of these technologies argue that China should take advantage of its abundant reserves to reduce their demand for imported energy. It is conceivably the combination of economic and energy security considerations that has encouraged the development of this coal conversion technology in China (Reuters, 2009). Thus, we choose these four technologies for this research.

System optimization model

3.1 Model framework

The model framework for China's liquid fuel industry contains three levels: resources (crude oil, biomass, oil shale, and coal), technologies, and products. The conversion technologies (refinery, liquid fuel plants, etc.) are the links between different levels. The details of the three levels are introduced in the following paragraphs.

Resources level: Resources include biomass, oil shale, coal, and crude oil, and these are either exploited domestically or imported from abroad. China's energy structure has rich coal resources, scarce crude oil, sufficient oil shale, and available biomass; thus, in this research, crude oil includes domestic oil and imported oil, and the other resources come from China. Conversion: This level includes liquid fuel converted from crude oil, biomass, oil shale, and coal based on the relevant technologies (OR, BTL, STL, and CTL, respectively). Demand level: This level denotes the final products (diesel and gasoline) distributed to consumers and is identified with the demand for final products.

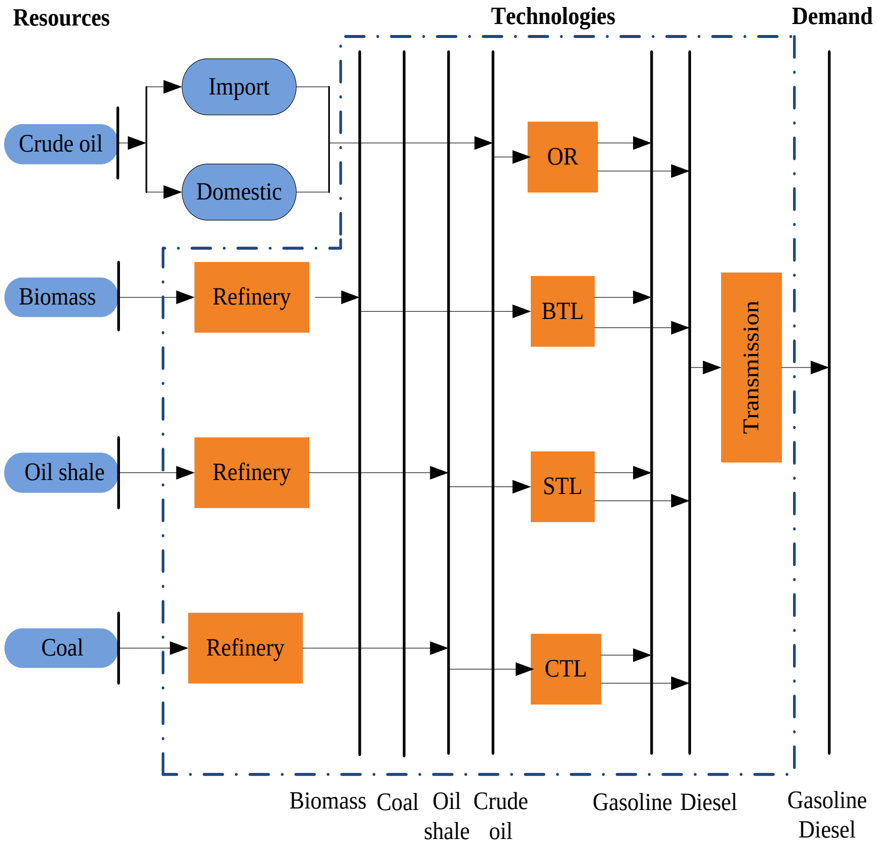

Figure 1. Different liquid fuel production chains

3.2. Definition of notations

The complete specification of the implemented model is summarized as follows.

Sets:

Indices and sets	Indices and sets definition
$i \in I$	Technologies
$t \in T$	Time period. $Tc \in T$ oil import constraint period
$k \in K$	Final products

Parameters:

Parameters	Parameter definition
ci_i^t	Investment cost
c_i^t	Installed capacity
$disc_t$	Capital recovery factor
τ_i	Plant life

η_i	Efficiency
σ	Discount rate
α_k	Demand annual growth rate
com_i	Operation and maintenance cost of liquid fuel production
c_i	Initial installed capacity per year
cap_i	Initial cumulative installed capacity
pr_i	Price of the resource
pc	Carbon price
$emif_i$	Emission coefficient
f_i^t	Annual operation time percentage for technology
m	Oil import dependency, with $0 \le m \le 1$
d_k^t	Exogenous demand $d_k^t = d_k^0(1+\alpha_k)^t$
$n_{i,k}$	The percent of final product *k* in the total output of technology *i*

Variables:

Variables	Variable definition
y_i^t	Newly installed capacity
$x_{i,k}^t$	Activity, representing the output of a certain technology, i.e., the product produced by a technology
tci	Total investment cost
tcr	Total raw material cost
$tcom$	Total operation and maintenance cost
tcc	Total carbon emission cost
r_i^t	The amount of raw materials consumed
cap_i^t	The cumulative installed capacity of technology

3.3 Model

The model is formulated as follows. The demand for diesel and gasoline is exogenous and increases over time, as shown in Equation (1). In Equation (2), η_i is the ratio of product energy consumption to total energy consumption. Product energy contains the energy of gasoline and diesel, and total energy consumption contains the energy of feedstock, steam, and electricity. The energies of gasoline, diesel, and feedstock are calculated based on their lower heating values. The consumption is shown in Equation (2). Equation (3) illustrates the process for calculating the cumulative installed capacity of technology i, which equals the summation of installed capacity and the initial cumulative installed capacity of technology. Installed capacity can be calculated as Equation (4); $\frac{\tau_i - t}{\tau_i} c_i$ denotes the remaining initial installed capacity of technology i. The continuous decision variables $x_{i,k}^t$ and y_i^t are nonnegative.

$$d_k^t = d_k^0 (1+\alpha_k)^t \ (k=1,2) \tag{1}$$

$$r_i^t = \max_k \left(\frac{x_{i,k}^t}{n_{i,k}} \right) / \eta_i \tag{2}$$

$$cap_i^t = cap_i + \sum_{l=t-plf_i}^{T} c_i^l \tag{3}$$

$$c_i^t = \begin{cases} \sum_t^T y_i^t + \frac{\tau_i - t}{\tau_i} c_i & t \le \tau_i \\ \sum_{l=t-\tau_i}^{T} y_i^l & t > \tau_i \end{cases} \tag{4}$$

Equations (5)-(8) formulate the four cost components. Equation (5) represents the total capital investment cost (tci) and is the multiplication of the capital investment per unit of production capacity and newly installed production capacity. The cost of raw materials equals the resource consumption amount multiplied by the resource price and discounted by the discount rate to the current price. The detailed calculation process can be seen in Equation (6). The O&M cost is determined by the output of the system, which is shown in Equation (7). The total carbon dioxide emission cost is calculated using Equation (8) and equal to the carbon price multiplied by the raw materials and the corresponding carbon emission factor. Equation (9) presents the outcome variable cost of our model, which includes investment cost (tci), raw material cost (tcr), O&M cost ($tcom$), and carbon emission cost (tcc). All costs occur in the future and consider the financial needs and resources of the country, so the annual discount rate is assumed to be fixed.

$$tci = \sum_{i \in I} \sum_{t \in T} disc_t \cdot ci_i^t \cdot y_i^t \tag{5}$$

$$tcr = \sum_{t \in T} \sum_{i \in I} disc_t \cdot pr_i \cdot r_i^t \tag{6}$$

$$tcom = \sum_{i \in I} \sum_{t \in T} disc_t \cdot com_i^t \cdot \max_k \left(\frac{x_{i,k}^t}{n_{i,k}} \right) \tag{7}$$

$$tcc = \sum_{i \in I} \sum_{t \in T} disc_t \cdot pc \cdot emif_i \cdot \max_k (\frac{x_{i,k}^t}{n_{i,k}}) \tag{8}$$

$$\mathrm{Cos}\,t = tci + tcr + tcom + tcc \tag{9}$$

Thus, the general form of the liner programming model is as follows. The objective function is Equation (10) and the constraints on the objective function are Equation (11)-(15).

$$\min \mathrm{Cos}\,t \tag{10}$$

$$d_k^t - \sum_{i \in I} x_{i,k}^t \le 0, \quad k \in K, t \in T \tag{11}$$

$$f_i^t \cdot c_i^t - \max_k (\frac{x_{i,k}^t}{n_{i,k}}) \ge 0, \quad i \in I, t \in T \tag{12}$$

$$r_{OR}^t - a \le m * r_{OR}^t, \quad t \in Tc, k \in K \tag{13}$$

$$x_{i,k}^t \ge 0, \quad i \in I, t \in T, k \in K \tag{14}$$

$$y_i^t \ge 0, \quad i \in I, t \in T \tag{15}$$

The objective function of our model is to minimize the accumulated total system cost, which can be presented as Equation (10). Equation (11) means that the demand of the k-th final product must be satisfied by the total output of the different technologies. Constraint Equation (12) ensures that the production should be no more than the installed capacity. Constraint Equation (13) requires that the amount of import oil must represent less than m percent of total oil from 2036 to 2045. Constraint Equation (14)-(15) mean decision variables are nonnegative.

Data collection and parameter assumptions

Development plans in China are commonly made annually. In our study, we consider 6 connecting five-year plans, from 2015 to 2045 with a time step of 1 year, as the decision periods of the optimization problem. The year 2015 is assumed to be the base year, and the annual discount rate is assumed to be 6%.

4.1. Demand for diesel and gasoline

From Figure 2, we can obtain China's consumption of diesel and gasoline in the last twenty years: 175 Mtoe and 119 Mtoe, respectively, in 2015, with average respective growth rates in demand of 7.4% and 5.3% during the period from 2000 to 2017. According to the national policy in 14th Five-Year Plan, the gasoline demand of China will continue to grow before 2030 then level off after 2030. Meanwhile, the diesel demand will step into a period of decline then level off after 2030. Therefore, in our study, we assume that the model will meet increasing demand at the annual growth rates of 1.0% and -2.0% for diesel and gasoline, respectively in 2016-2030, which will be 0.2% and -0.3%, respectively in 2031-2045 (Xing and Luo, 2020).

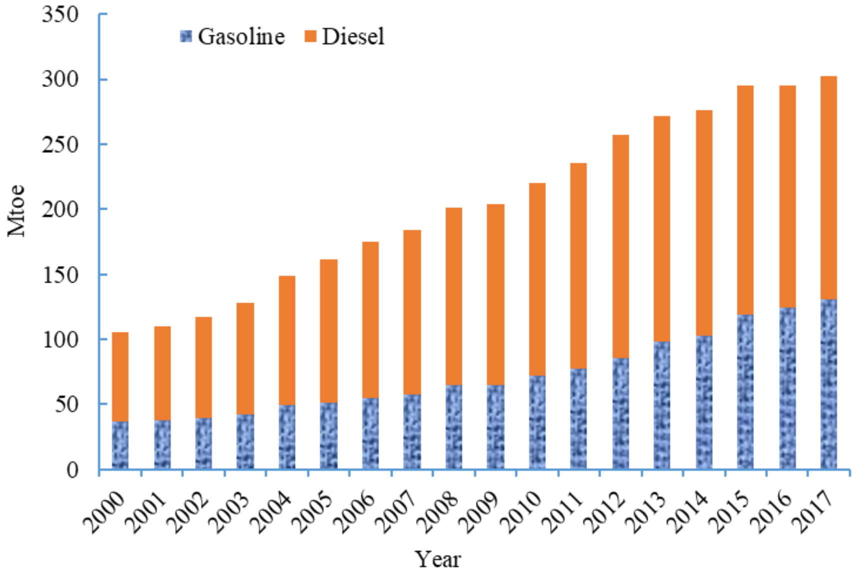

Figure 2. The consumption of diesel and gasoline in China from 2000 to 2017

4.2. Feedstock prices in the base year

Table 1 presents the prices of resources used to produce liquid fuels. These data were obtained from the National Bureau of Statistics of China and China Industry Research. As discussed in the introduction, this study focuses particularly on how China should compose raw materials and different production technologies to meet the given liquid fuel demand and objectives. For this purpose, we assume that the feedstock prices as inputs to these technologies will be constant.

Table 1 Feedstock prices in the base year

Year	Oil[a] US$/toe	Coal[b] US$/toe	Biomass[c] US$/toe	Oil shale[d] US$/toe
2015 (base year)	357	83	289	94

[a] Crude oil price is converted from the National Bureau of Statistics of China (NBSC, 2016).

[b] Coal price is converted from the National Bureau of Statistics of China (NBSC, 2016).

[c] Data on biomass are converted from Dimitriou et al. (2018).

[d] Data on biomass are converted from Zhou et al. (2016).

Table 2 shows the capacities of the four technologies in 2015 and the new expansion capacity from 2016 to 2020 in China. From this, we can see that OR dominated liquid fuel production in 2015 and accounted for approximately 94% of the total production, while CTL was the second most widely used liquid fuel production technology in China in 2015.

Table 2 Capacities of the four production technologies in 2015 and capacity expansion planned in 2016-2020 in China

Technologies	Total capacity in 2015 (Mtoe) [a]	Share of technologies in 2015	Capacity expansion planned in 2016-2020	Cumulative installed capacity in 2015

			(Mtoe)[b]	(Mtoe)[a]
BTL	0.6	0.8%	0.7	0.7
CTL	2.5	3.5%	9.5	3.0
STL	1.1	1.5%	2.0	1.4
OR	70.0	94.2%	20.0	73.4

[a] The BTL capacity data were taken from BP (2016), the CTL capacity data were taken from Li (2017), the STL capacity data were taken from the National Energy Administration of China (2017), and the OR data were taken from Zhou et al. (2019).

[b] These data were taken from the National Energy Administration of China (2017).

Table 3 Technoeconomic parameters of the liquid fuel industry.

Technology	Feedstock	Investment cost [a] (US$/toe)	C_{OM} cost [a] (US$/toe yr)	Efficiency [a] (%)	Total CO2 emissions [b] $t_{CO2}{\bullet}t^{-1}$	Plant factor [a] (%)	Plant life (yr)[a] (yr)	Construction time (yr) [a] (yr)	Percent of gasoline [c] (%)	Percent of diesel [c] (%)
BTL	Biomass	1106	334	34	4.7	80%	20	3	34	66
CTL	Coal	1397	380	46	15.5	80%	20	4	25	75
STL	Oil Shale	532	392	26	9.8	80%	15	2	16	84
OR	Crude oil	509	89	79	6.4	80%	20	3	37	63

[a] 2018US$/¥ = 7. The CTL investment cost data were calculated from Zhou et al. (2018), the investment cost of OR is from BP (2016), and the STL investment cost data are calculated from Zhou et al. (2019). The BTL investment cost was taken from Larson et al. (2010).

[b] These data were taken partly from a recent review by Zhou et al. (2018), and the BTL emission data were assumed based on biomass cracking emissions from Yang et al. (2019).

[c] These data were taken partly from a recent review by Larson et al. (2010), and the BTL data are from Zhou et al. (2016).

Following the optimization model framework, in our study, liquid fuel technologies are characterized by their initial investment cost, O&M cost, energy efficiency, CO2 emissions coefficient (i.e., total CO2 emission per ton liquid fuel), plant factor, construction time, and plant life. Table 3 summarizes these technoeconomic parameters.

Scenario analysis

Due to carbon price is an efficient policy that can address the externalities of energy use, and oil import dependency is an important factor in evaluating energy security, thus, we designed the following four scenarios for carbon price and oil import dependency, where the carbon price is obtained from China Carbon Trading Exchange, and the current oil import dependency is calculated based on the data collected from the National Bureau of Statistics.

5.1 Four scenarios

According to the National Bureau of Statistics, the annual domestic crude oil production of China has not fluctuated substantially in the past ten years. Thus, we assume that the amount of domestic crude oil that is used to make liquid fuel will not change in this research. In 2015, in the total consumption of crude oil, which is used to make liquid fuel, nearly 40% is domestic crude oil, thus in this research a= $4.5*10^4$ toe (NBS, 2020).

(Al) Scenario A1. Scenario A1 is the reference scenario in which the carbon price is 30 $/toe and oil import dependency is not considered. This scenario assumes that China can import oil from overseas as usual to satisfy its demand.

(A2) Scenario A2. In this scenario, we assume that the carbon price increases to 100 $/toe, while there is no consideration of oil import dependency. This scenario represents the idea that the government wants to encourage energy conservation and emission reduction and promote the development of the renewable energy industry to drive an increase in the carbon price.

(A3) Scenario A3. In this scenario, oil import dependency must decrease to 60% after 2035, and the future carbon price will be 30 $/toe.

(A4) Scenario A4. In this scenario, the carbon price is set as 100 $/toe following the China Economic Net (2019), and oil import dependency is set to 60% after 2035.

The liquid fuel industry could reduce its carbon emissions and oil import dependency by implementing the best portfolio of technologies and R&D efforts in renewable energy. In the following, we present and discuss the optimal results of these four scenarios. Then, we conduct a sensitivity analysis on the carbon price and oil import dependency based on the four scenarios.

5.2 Result under the four scenarios

Solving with MATLAB, we obtained the optimal results of the four scenarios, such as the capacity configuration of different technologies, the accumulated total system cost, and the consumption of feedstocks in the four defined results scenarios.

5.2.1 Capacity configuration of different technologies

Table 4 gives the capacity configuration of different the technologies for liquid fuel production in the four scenarios over the study period (2016-2045). The results show that in some scenarios, OR will remain the most significant over the next three decades, and CTL will develop faster in scenarios A1 and scenarios A3. Meanwhile, in Scenario A1 and Scenario A3, approximately 5%-17% of China's liquid fuel production will use CTL technology. The capacity of BTL also expands rapidly in the study period in all four scenarios, especially scenario A2, scenario A3, and scenario A4. BTL technology mainly consumes biomass and is expected to reduce carbon emissions with respect to fossil fuel processes. Therefore, the higher the carbon price is, the higher the percentage of BTL. Otherwise, considering the dependence on oil imports, the percentage of BTL will expands more rapidly. The results of the scenarios suggest the competitive strength of BTL and CTL technologies given different carbon prices and oil import dependency.

Table 4 The percentage of capacity configuration for different technologies in the four scenarios

Scenarios	BTL	CTL	STL	OR
A1	5.4%	5.8%	1.8%	87.0%
A2	18.0%	3.7%	1.3%	77.0%
A3	22.8%	17.3%	3.8%	56.1%
A4	28.8%	3.3%	1.2%	66.7%

Figure 3 presents the capacity expansion of different technologies in the four scenarios from 2016 to 2045. From Figure 3, we can see that in scenario A1, the total expansion capacity will reach 124.7 Mtoe in 2020, consisting of approximately 0.8 Mtoe BTL, 6.5 Mtoe CTL, 2.4 Mtoe STL, and 115.0 Mtoe OR. During 2021-2045, the liquid fuel production technologies CTL and BTL capacity will expand considerably, and STL will see a small capacity expansion. Accordingly, the contribution of CTL to the expansion capacity is more than 5.8% in the reference scenario. For 30 years, the total accumulated expansion capacity of all technologies will reach 132.4 Mtoe in scenario A1. In scenario A1, the expand capacity grown faster in the first five periods, then the growth trend level off.

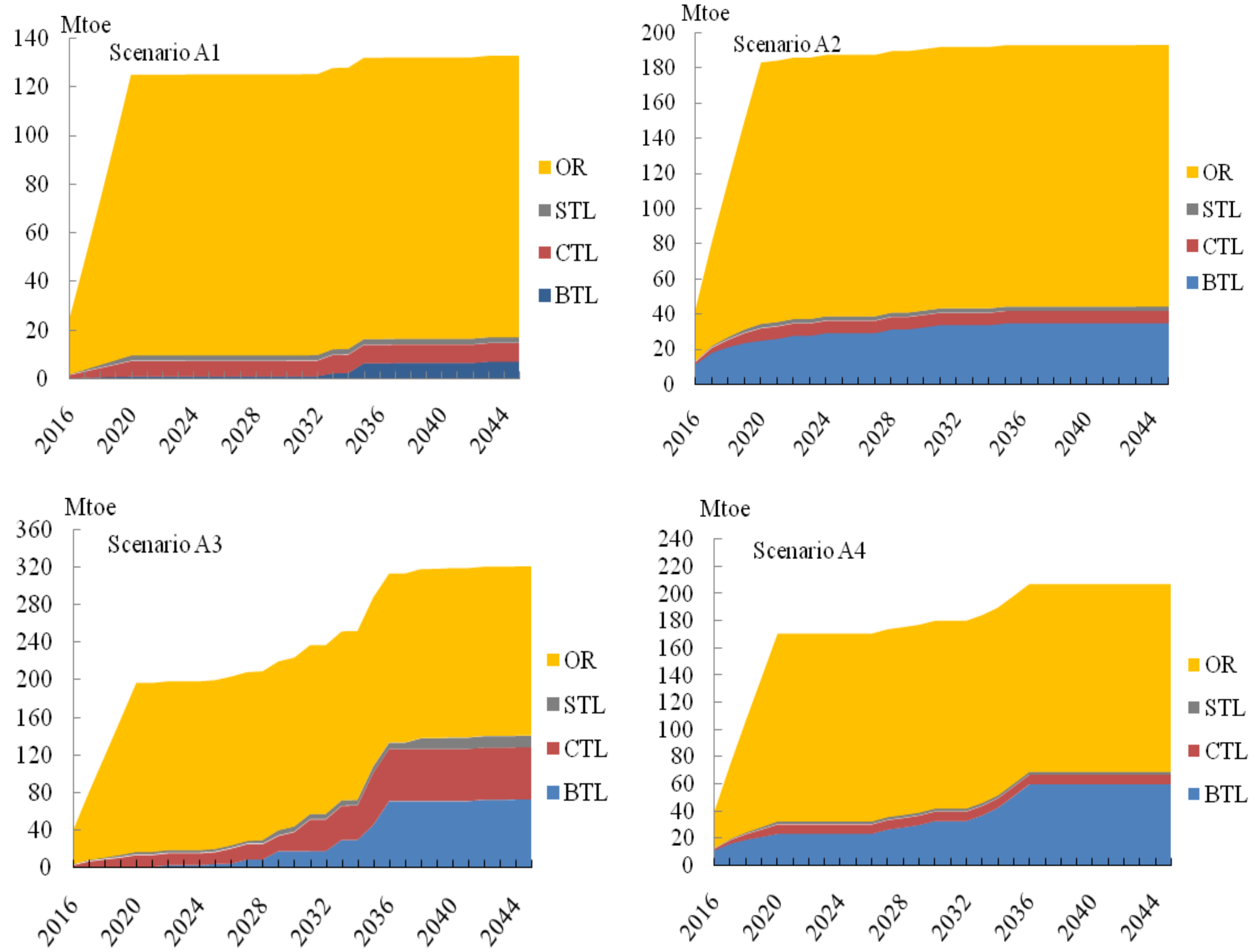

Figure 3. Capacity expansion of different technologies in scenarios Al, A2, A3, and A4

In Scenario A2, as shown in Figure 3, the total new capacity expansion will reach up to 183.1 Mtoe before 2020, consisting of approximately 25.0 Mtoe BTL, 7.0 Mtoe CTL, 2.5 Mtoe STL, and 148.6 Mtoe OR. During 2021-2045, the capacity of BTL will expand considerably compared to that of CTL, accounting for approximately 18% of the total expansion capacity, while STL only sees a small capacity expansion within liquid fuel production technologies. From 2016 to 2045, the accumulated capacity expansion will amount to 193.0 Mtoe, which is higher than the capacity in scenario A1.

From Scenario A3, we can see that the total new capacity expansion will reach 197.0 Mtoe before 2020, consisting of approximately 1.4 Mtoe BTL, 12.5 Mtoe CTL, 3.1 Mtoe STL, and 180.0 Mtoe OR. Meanwhile, during 2021-2045, the capacity of CTL and BTL will expand considerably, accounting for approximately 22.8% and 17.3% of the total expansion capacity, but STL only has a minor capacity expansion. In scenario A3, the expansion percentage of BTL and CTL are higher than those in the other scenarios, and the expansion capacity of them are also higher than those in the other three scenarios. From 2016 to 2045, the accumulated capacity expansion will amount to 321.2 Mtoe, which is higher than the capacity in scenarios A1 and A2.

In Scenarios A2 and A4, BTL will account for 18.0% and 28.8%, respectively, of the accumulated capacity expansion. BTL has advantages in those scenarios because it has lower carbon emissions. In scenario A4, the expansion percentage of BTL is higher than that in the other scenarios, but the expansion capacity of the technology is lower than that in scenario A3. The total capacity expansion over the study period will amount to 207.2 Mtoe, which is higher than that in scenario A1 and scenario A2, but lower than that in scenario A3.

5.2.2 The total system cost

Figure 4 shows the total system cost and the percentage of each cost in the total from 2016 to 2045 in the four scenarios. As mentioned above, the total system cost consists of investment cost, feedstock cost, O&M cost, and carbon cost based on the capacity expansions of different technologies. In all scenarios, feedstock cost occupies the largest portion of the total system cost. In scenario A1, the minimum total system cost for 30 years is 1464 million US$. The feedstock cost accounts for approximately 56.8% of the total system cost. When the carbon price is 30 $/t, the carbon cost will account for 25.6% and 25.1% of the total system cost in scenarios A1 and A3, respectively.

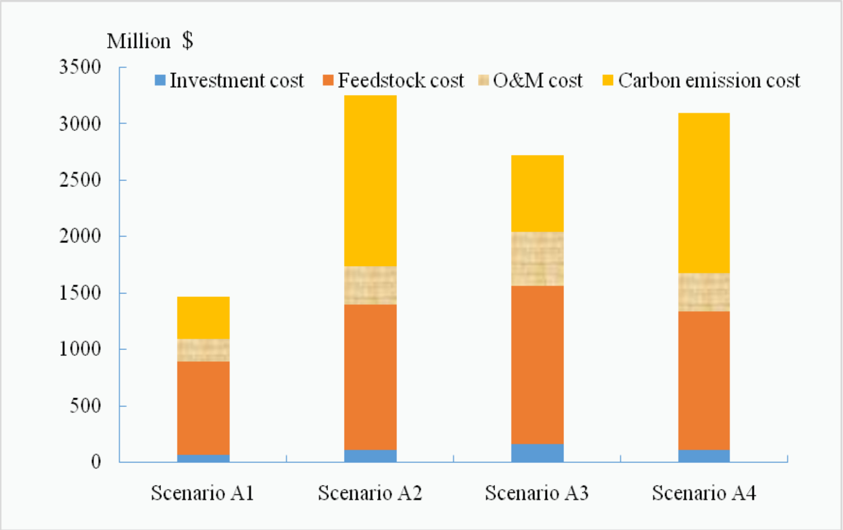

Figure 4. Total system cost of the four scenarios

In Scenarios A2, A3, and A4, the total system cost is approximately 3255 million US$, 2722 million US$, and 3093 million US$, respectively. Accordingly, scenario A2 and scenario A4 show an increase from scenario A1. The increase in the carbon price is the reason for the rise in the total system cost. In scenario A3, the decrease in oil import dependency leads to the slow capacity expansion of OR and the rapid capacity expansion of BTL and CTL, so the capacity of CTL and BTL accounts for 17.2% and 22.8% respectively of all technologies in scenario A3. However, both biomass and coal have a low feedstock price and a lower carbon price in this scenario, but the more adoption of CTL technology need to put much more investment cost and O&M cost, therefore, the total system cost in scenario A3 is also higher than that in the scenarios A1. Apart from the high carbon price in scenario A4, considering oil import dependency will accelerate the adoption of BTL and reduce the adoption of CTL and OR. BTL has lower investment cost, O&M cost and carbon emission than CTL, thus, the total system cost of scenario A4 is lower than scenario A2. In brief, the decrease in oil import dependency will accelerate adoption of renewable resources and clean technology, but the carbon price increase will increase the total system cost substantially.

5.2.3 Sensitivity analysis

In the four scenarios mentioned above, carbon price and oil import dependency greatly influence the adoption of BTL and CTL. Thus, in the sensitivity analysis on carbon prices, we first compare the adoptions of BTL and CTL under different carbon prices ranging from 0 to 160 $/toe with a step of 40, as shown in Figure 5. The results show that changing the carbon price leads to the greater adoption of BTL technology, which is very sensitive to the carbon price, especially when the carbon price is more than 40 $/toe. When the carbon price is 0 or 40 $/toe, the percentage of BTL is almost 0 before 2035. High carbon prices can lead to a rapidly increase in the percentage of BTL; for example, when the carbon price is 160 $/toe, the share of BTL has a quickly increase during 2015 to 2035, and then it stabilizes. In this scenario, since oil import dependency is not considered, BTL technology benefits significantly from high carbon prices and takes large account of liquid fuel industry after 2035.

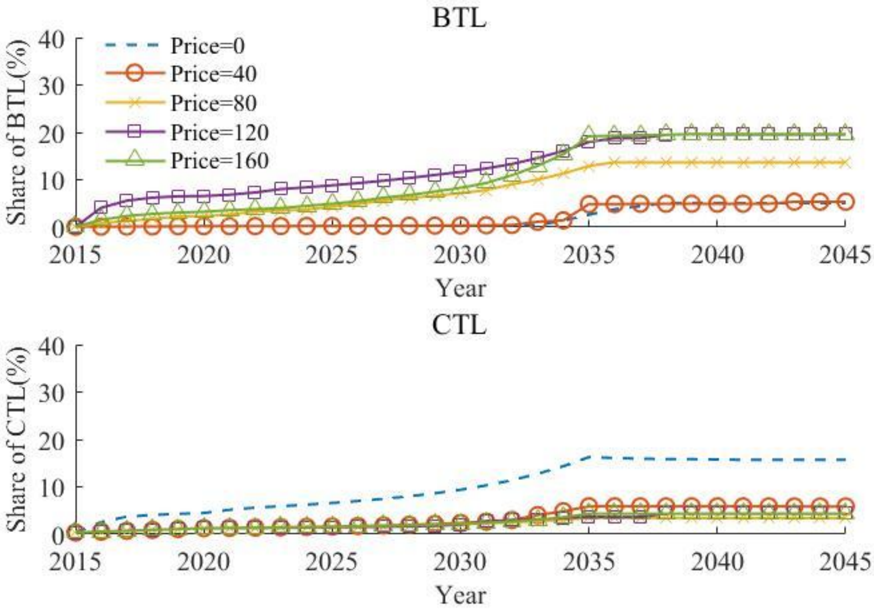

Figure 5. Adoption of BTL and CTL technology with different carbon prices in scenario 2

Unlike BTL technology, CTL production has high carbon emissions; thus, CTL technology develops faster when the carbon price is 0 , and the higher the carbon price is, the lower the share of CTL. However, changing the carbon price from 80 \$/t to 160 \$/t does not affect the share of CTL much, and in 2045, the share of CTL is approximately 4% under different carbon prices. As mentioned above, feedstock cost represents the largest percentage of total system cost, so even when the carbon price reaches as high as 80 \$/t, CTL will occupy a certain percentage among the four technologies due to the low feedstock price.

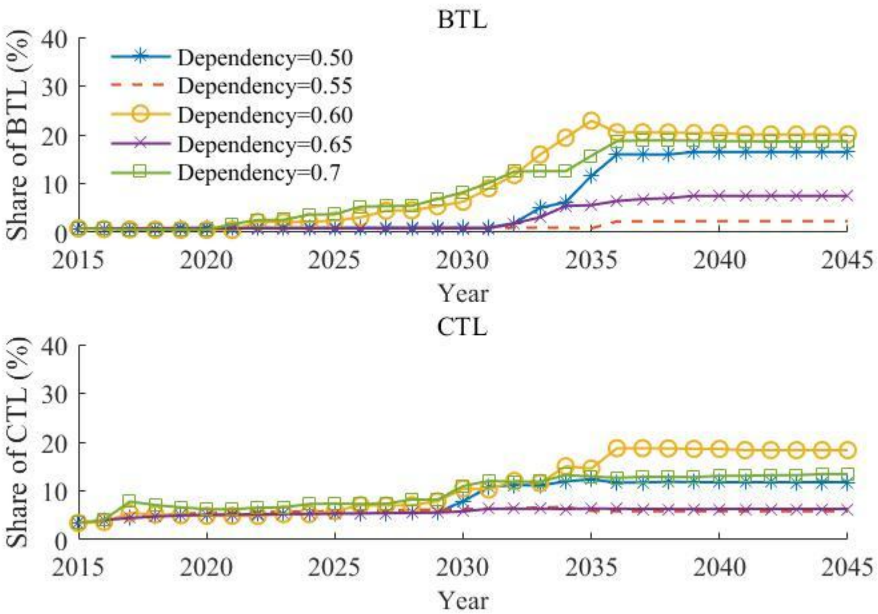

Figure 6. Adoption of CTL and BTL technology with different oil import dependencies in scenario 3

Figure 6 plots the adoption of STL and CTL technology with different levels of dependence on oil imports in Scenario

A3. The percentage of CTL is nearly 4% before 2030, and CTL technology will develop faster, especially when the oil import dependency is 60%. While the lower level of dependence on oil imports does not cause a higher share of BTL, this special situation is mainly due to the rapid development of CTL and STL technologies. Compared with CTL technology, BTL technology develops very slowly before 2030, but it develops rapidly between 2030 and 2036, after which its development speed will slow.

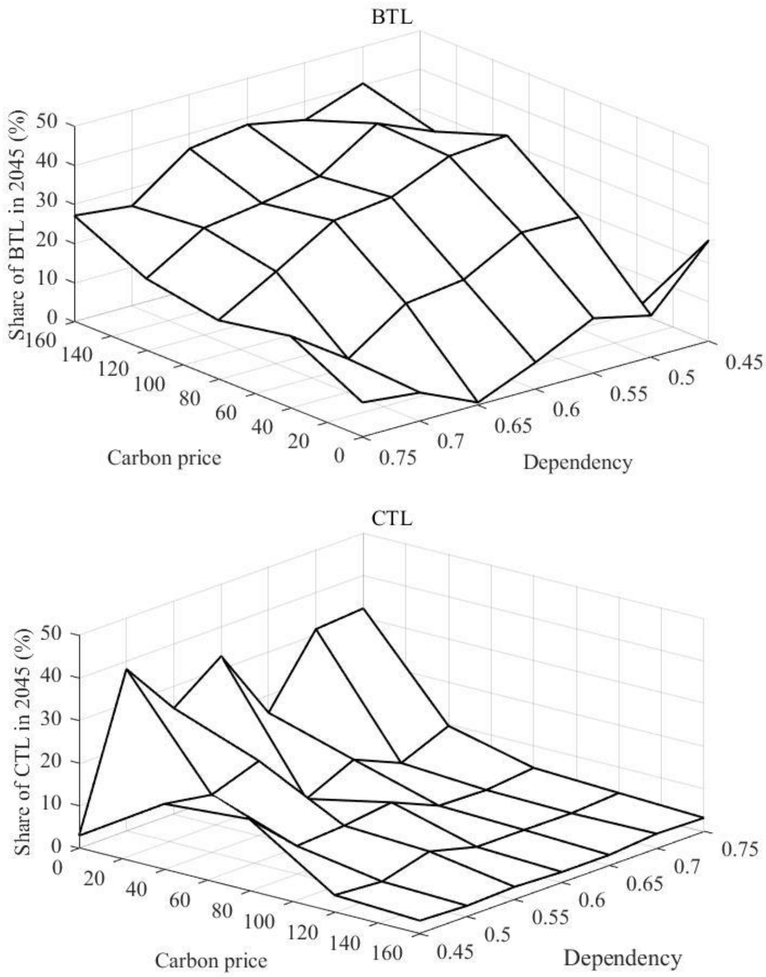

Figure 7. Adoption of CTL and BTL technology with different carbon prices and oil import dependencies in scenario 4

With scenario A4, we experiment with different combinations of carbon prices and oil import dependencies. Figure 7 shows the adoption of BTL and CTL in 2045 with different combinations and indicates that carbon prices will greatly influence their adoption. The higher the carbon price is, the lower the share of CTL and the higher the share of BTL. When the carbon price is above a certain level, a further increase in the percent has little influence on the adoption of CTL and BTL.

Oil import dependency is also a mechanism for the adoption of new technologies, although its effect is weaker than that of carbon prices. Otherwise, the share of BTL and CTL adoption is not monotonically increasing with the decrease in oil import dependency. For example, in Figure 7, when the carbon price is 160 and the oil import dependency decreases from 70% to 65%, there is an obvious decrease in BTL technology. Meanwhile, when the oil import dependency is below a certain value, the percent has little influence on technology adoption, especially the adoption of CTL.

Conclusion

This study developed an optimization model to explore how China should configure its liquid fuel industry from 2015 to 2045 under four different scenarios for carbon prices and the level of dependence on oil imports. The preliminary results showed that without considering controls on oil import dependency and with low carbon price, CTL will be competitive and play a significant role in China's liquid fuel production; otherwise, the adoption of CTL will be restrained, and the share of BTL will be higher than that of CTL. The decrease in oil import dependency does not necessarily promote the wide adoption of CTL and BTL, but it can strengthen the effect of carbon prices in terms of adopting more CTL and BTL. Therefore, the decision to develop BTL and CTL is not incorrect because it will be important in China's liquid fuel production industry in the future, especially in terms of reducing dependency on crude oil since more than 60% of the crude oil consumed is imported from overseas.

Our study further implies that reducing the level of dependence on oil imports might also be a good decision for reducing the system total cost, since it could lead to the selection of renewable resources and clean technology. Of course, policymakers should be cautioned that a number of concerns about the uncertainties of new technologies remain to be addressed. For private investors who are considering investing in China's liquid fuel industry, our study provides insights into the technologies that could be competitive and worth investing in and the appropriate capacity configurations.

In future work, with the model framework proposed in this paper, we will use multicriteria analysis to research energy security, carbon emissions, and total cost and explore how technological learning, demand, water consumption and feedstock price influence the adaptation of different technologies.

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