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A comparison between coal-to-olefins and oil-based ethylene in China: An economic and environmental prospective

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ABSTRACT

Recently, many coal-to-olefin (CTO) plants have started up in China. It is important for China to answer the following question: between coal-based ethylene and oil-based ethylene, which is the better choice? To provide a reference for policy makers and investors, this paper analyses the economic performance and the impact of future environment policy of both the CTO project and the oil-based ethylene project by a cost-benefit analysis. Quantitative analysis shows that the CTO project has a slight advantage over the oil-based ethylene project in a basic scenario when the crude oil price is above $70/bbl. However, international oil prices have a greater impact on the CTO project than the oil-based ethylene project. Thus, the CTO project has less anti-risk ability to the international oil market fluctuation than the oil-based ethylene project. What's more important is the environmental policy impact. After taking carbon trading costs and wastewater surcharge into account, the CTO project no longer has any advantage over the oil-based ethylene project. It can be seen in the foreseeable future that the CTO project will soon lose competitiveness. This indicates that the CTO project may not be consistent with sustainable development. These results suggest that from an environment perspective, policy makers and investors should be prudent about developing the CTO project.

1. Introduction

As the representative of light olefins, ethylene is the basic raw material in the petrochemical industry. In 2016, China produced 17.8 million tons of ethylene (National Bureau of Statistics of China (NBSC), 2017a). However, China has demand for more than 40 million tons of ethylene. It means more than 50% of the ethylene or ethylene products need to be imported from other countries. This fact has made Chinese enterprises believe that the domestic ethylene market still has space to share. With most of the ethylene coming from naphtha as shown in Fig. 1 (Chunmei, 2016), this point of view has drawn unprecedented attention since 2011 because of the sharp fluctuations in crude oil prices. Ministry of Industry and Information Technology predicts China will consume 48 million tons of ethylene in 2020 (Ministry of Industry and Information Technology of China (MIITC), 2016). Thus, about 70 million tons of naphtha are needed if the self-sufficiency rates of ethylene remains 50%. However, only 32.8 million tons of naphtha were produced domestically in 2016 (National Bureau of Statistics of China (NBSC), 2017b). Oil production in China has even been shown to have peaked or to be on the verge of peaking (Wang et al., 2016).

Coal accounts for about 63.7% of China's energy consumption in 2015 (BP, 2016), making it far more important than other energy resources. China produced 3.4 billion tons of coal in 2016 (National Bureau of Statistics of China (NBSC), 2017c). Even if half of the domestic ethylene is produced from coal, there are only 3.8% of the domestic coal production consumed. Although studies show China's indigenous coal supplies are now falling short of the amount needed to support the economic growth (Wang et al., 2013), the importance of coal can hardly be replaced in short time.

Controversies about the coal chemical industry have not ceased (Pan et al., 2012; Xie et al., 2010). Over the past few years, air and soil pollution along with the water resources shortage has become increasingly serious in China (Sun et al., 2016). The voice of environmental protection is getting louder. The problem of environmental protection is gaining more attention. In the field of carbon emissions and environmental problems, the coal chemical industry has been criticized by many experts. On April 24, 2014, the eighth meeting of the twelfth session of the NPC Standing Committee

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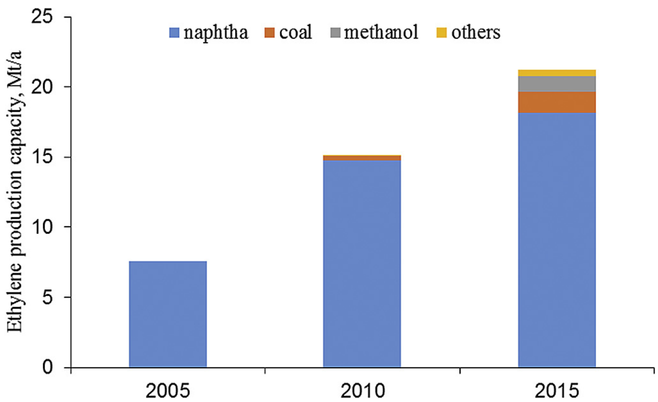

Fig. 1. Raw material of ethylene in China.

voted for the “Environmental Protection Law Amendment”. The new environmental protection law was implemented on January 1, 2015, which indicates that China's protection of the environment will reach a new height. Many coal chemical enterprises will have to implement more stringent environmental standards, especially in the treatment of coal gasification wastewater (CGW).

Carbon dioxide emissions will also become a heavy burden on coal chemical enterprises. China made a commitment in late 2009 to achieve a carbon intensity decrease by 40%–45% of the 2005 level by 2020 (Cui et al., 2014). In June 2015, China officially submitted its intended nationally determined contribution (INDC) to the UNFCCC, which added a target to cut CO_2 emissions per unit of GDP by 60–65% of the 2005 level by 2030 to the earlier pledge to peak CO_2 emissions and increase the non-fossil share in primary energy consumption to 20% by the same year (Zhang et al., 2016). To achieve the objectives above, China has carried out carbon trading work in several large cities such as Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangzhou and Shenzhen (Xiong et al., 2015). Carbon trading in China has not yet been widely implemented, but coal chemical enterprises will inevitably cut or trade carbon emissions in the foreseeable future. Coal chemical enterprises are likely to bear a certain cost due to the huge carbon emissions.

Given the potential importance of CTO industry to olefins industry and sustainable development, a systematic study is necessary to compare the oil-based ethylene project and CTO project. Xiang et al. (Xiang et al., 2014a) made an overall comparative techno-economic analysis of a CTO plant and an oil-to-olefins (OTO) plant based on process simulation. They focused on three criteria including energy efficiency, capital investment, and product cost. It's found that the CTO plant takes advantage over the OTO plant from a cost analysis perspective. The cost advantage will be further enlarged in terms of international feedstock prices in future. Carbon tax has a serious impact on CTO plants. However, results show the competitive strength of the CTO plant will be still present even the carbon tax is increased to as high as 310 RMB/t CO_2. Besides, they (Xiang et al., 2014b) conducted a detailed techno-economic analysis of the CTO process with CCS. Economic performance and environmental impact were studied comprehensively. CTO processes with appropriate CO_2 reduction are found to be more applicable to olefins industry than MTO processes in China. Qian et al. (Qian et al., 2015) proposed an integrated process of coke-oven gas and coal gasification to methanol, achieving high carbon utilization and energy efficiency. To reduce high CO_2 emission of a coal-to-olefins process, Yang et al. (Yang et al., 2013) proposed a new natural gas assisted coal-to-olefins process integrating CO_2 recovery gasification and CH_4/CO_2 reforming techniques. Man et al. (Man et al., 2014b) proposed a novel co-feed process of coke-oven gas assist CTO in which CH_4 of coke-oven gas reacts with CO_2 to reduce emissions. Man et al. (Man et al., 2014a) analyzed coal gasification with/without CO_2 capture processes from environmental, technical, and economical points of view. The results show that the coal gasification process with CO_2 capture and sequestration has advantage only in environmental aspect compared to the conventional process. The process with CO_2 capture and utilization has advantages in both technical and environmental aspects while disadvantage in economic aspect. Zhou et al. (Zhou et al., 2015) introduces energetic and economic penalties to calculate the costs for closing the CO_2 loop of CTO projects in China. It is found that Gansu, Ningxia, and Sinkiang suffer from the highest penalties. Thus, the expansion of coal-based projects in these regions should be limited. Ren et al. (Ren et al., 2008) made a comparative analysis of olefins production from oil and natural gas. While several possibilities for energy efficiency improvement do exist, the natural gas-based routes can hardly become more energy efficient than steam cracking routes do at present. The natural gas-based routes also lead to more CO_2 emissions. Xiang et al. (Xiang et al., 2015) conducted a comparative study of alternative olefins production from coal, natural gas, and coke-oven gas. By introducing hydrogen-rich gas, the co-feed systems ensure the effective utilization of coal, great reduction of CO_2 emissions, and improving energy efficiency.

Coal and oil are the most important petrochemical raw materials in China. Most of the previous studies focused on cost analysis of olefins projects. In contrast, the comparative analysis of the benefits is less mentioned. It is thus necessary to introduce economic indicators to comprehensively compare the CTO project and the oil-based ethylene project. International oil prices have a great influence on China's petrochemical project, yet scholars did not pay much attention on this issue. Accordingly, detailed work on this subject needs to be supplemented. When it comes to environmental protection and CO_2 emissions, the two kinds of olefins projects can also be clearly compared from a cost-benefit perspective.

This paper focuses on calculating under what circumstances the CTO route has more advantages than the oil-based ethylene route and under what circumstances it will not. Net present value (NPV) and internal rate of return (IRR) are the key economic indicators of the two projects, since these two indicators directly determines whether a project is profitable. In recent years, the international oil prices have fluctuated violently. The impact of market fluctuation on the two kinds of project is also assessed in this paper. What should be paid more attention is that environmental problems in China are getting worse. Increasingly stringent environmental policies will put higher demands on coal chemical industry especially in wastewater treatment. As an important national policy, carbon emission reduction also has an important impact on the two routes. As indicated above, wastewater treatment and carbon trading were taken into consideration.

This paper is organized as follows. Section 2 illustrates technical routes of the oil-based ethylene project and the CTO project. Section 3 sets up the model of the two types of routes including product output and fixed costs. Section 4 shows the economic comparison between the two routes. Section 5 explores how the competitiveness of these two types of ethylene projects change with fluctuations in the prices of crude oil and coal during the years. Wastewater surcharge and carbon trading costs are also included in this section. Section 6 provides the main conclusions and policy recommendations.

2. Technical routes

In a naphtha steam cracking process, naphtha is first cracked into gas. The cracking gas is then fed into gasoline splitter to separate gasoline and fuel oil. Then the light gas is separated into pure ethylene and propylene via separation equipment. The diagram of a CTO process is shown in Fig. 2. A CTO process contains three main sub-processes, including coal gasification, methanol synthesis, and olefins synthesis. As showed in Fig. 2, the coal is mixed together with oxygen into the gasifier to produce syngas. The syngas is then fed into the CO shift unit to increase the ratio of H/C. Before methanol synthesis, the syngas is cleaned in the acid gas removal unit to remove H_2S and CO_2. The syngas then goes to the methanol synthesis unit to produce methanol. The methanol goes to the methanol to olefins reactor to be converted into olefins.

A number of coal-to-olefins (CTO) processes have been developed. The representatives of them are ExxonMobil MTO, UOP/Hydro MTO, DMTO and DMTO–II developed by Dalian Institute of Chemical Physics of Chinese Academy of Science, SMTO and SMTP by Sinopec, Lurgi MTP, and FMTP by Tsinghua University (Cai et al., 2016; Chen et al., 2005; Ren et al., 2008; Rothaemel and Holtmann, 2002). Shenhua Group successfully applied DMTO technology to produce olefins by coal based methanol in January 2011. It is China's first CTO plant. The DMTO technology is considered as world leading and the production process has been stable for years. The product composition of the two projects is shown in Table 1 according to the work of Wu (Wu, 2014).

Table 1
Product composition of the oil-based ethylene project and the CTO project.

Feedstock	Naphtha (wt%)	Coal (wt%)
Ethylene	28.10	39.12
Propylene	15.00	38.06
Butadiene	9.00	10.15
Light paraffin(C1~C4)	20.90	5.58
Mixtures of C5	3.25	–
Crack gasoline	22.50	2.88
Others	1.25	4.12

3. Economic analysis

3.1. Costs

As shown in Table 2, the following is the production costs of the CTO and oil-based ethylene projects.

Table 2
Basic scenario model parameters.

	Unit	Feedstock	
		Naphtha	Coal
Fixed costs			
Debt: Equity		3:1	3:1
Land and construction	MRMB	4575	4250
Plant life	yr	15	15
Financial expenses	MRMB/yr	1413	1390
Credit period	yr	15	15
Discount rate	%	3[a]	3[a]
Operating and maintenance (O&M)	MRMB/yr	259[b]	255[c]
Variable costs			
Raw materials	kt/yr	3560	4250
Naphtha price	RMB/t	5500[d]	–
Coal price	RMB/t	–	405[e]
Catalysts and Chemicals	MRMB/yr	50	200
Utility	MRMB/yr	585	600
Value-added tax rate	%	17	17
Construction tax rate	% (Value-added tax)	7	7
Education surcharge rate	% (Value-added tax)	5	5

Note: This table goes through the basic scenario calculations.
[a] The discount rate can be approximately equal to Producer Price Index (PPI), which is a is a price index that measures the average changes in prices received by domestic producers for their output. In China, PPI has floated around 3% in recent years.
[b] Operating and maintenance costs include staff wages and management costs. Staff wages cost 25 MRMB per year, assuming that the plant employs 500 employees, and per capita wages and benefits are 50 thousand RMB/year. Management costs 234 MRMB per year (including the company funds, union funds, staff education, labor insurance fees, and consulting fees).
[c] A CTO plant usually requires more staff then an oil-based ethylene plant. The CTO plant employs 1500 employees, and per capita wages and benefits are 50 thousand RMB/year. Management costs are 180 MRMB per year.
[d] Average quote for petrochemical companies in China (Shengyishe, 2016).
[e] Common mixed coal average price in China (Fenghuang, 2016).

3.1.1. Fixed costs

Fixed costs are divided into two categories, one is a one-time payment, and the other is amortization. Fixed costs do not vary with changes in the output value or production.

3.1.1.1. Land and construction costs. Usually, land and construction costs will be paid during the construction process. To simplify the calculation, land and construction costs are treated as a one-time payment, and it occurs in year zero. For a coal-based ethylene plant, a CTO plant with an ethylene capacity of 350 thousand tons per year needs 17 billion RMB to construct (Yong, 2014). For an oil-based ethylene plant, it was reported the construction costs was 18.3 billion RMB with an ethylene capacity of 1 million tons per year (Yang, 2009). The debt: equity ratio (D: E ratio) of the two project equals 3:1 in this paper. In the calculations, depreciation is not treated as a cost in this paper because depreciation expenses do not affect cash flow.

3.1.1.2. Financial expenses. These charges equal the repayment on the loan for the duration of the loan package. The interest rate is assumed to be 6% and equal installments are used in this study.

3.1.1.3. Operating and maintenance (O&M) costs. Operating and maintenance costs include staff wages and management costs. All O&M costs are treated as fixed costs in this paper.

3.1.2. Variable costs

Variable costs are based on the actual production or output value.

Raw material costs: Raw material costs are based on the raw

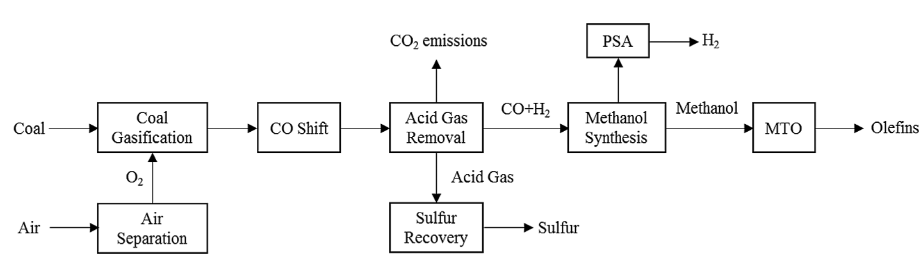

Fig. 2. The diagram of a CTO process.

material consumption quantity and price.

Utility costs: Utility costs are based on the total production capacity. Steam and electricity costs are the major part of utility costs.

Taxes: In China, there are four primary taxes for ethylene production enterprises. Value-added tax is based on the difference between the price of the raw material and products. The construction tax and education surcharge are paid according to the value-added tax.

3.2. Revenue

In the ethylene production process, these two projects will both produce many other valuable by-products. For the oil-based ethylene project, the product composition is very dispersive. Ethylene only accounts for approximately 28% of all of the products. For the CTO project, almost all of the products are concentrated on ethylene and propylene, with mass fractions of 39% and 38%, respectively. Because both of the projects will produce a large proportion of ethylene and propylene, these two products are treated the main products. In recent years, like the price of ethylene, the prices of by-products have been quite variable. This paper uses historical data to calculate the ratios of the by-products prices to the ethylene price (shown in Table 3) so that later calculations can be carried out when considering the price change of crude oil.

3.3. Economic indicators

In each operational year, the undiscounted net cash flow of a project is the cash received less the cash spent. The annual undiscounted net cash flow associated with an ethylene project in year t is computed as

$$NCF_t = R_t - FixEX_t - VarEX_t \tag{1}$$

where NCF_t denotes the annual undiscounted net cash flow in year t, R_t denotes the revenue in year t, $FixEX_t$ denotes the fixed costs in year t, and $VarEX_t$ denotes the variable costs in year t.

The sum of the discounted cumulative cash flow is equal to the net present value (NPV), which is a widely used economic indicator. The NPV is calculated as

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+i)^t} \tag{2}$$

where i represents the discount rate and n represents the producing life of the ethylene project. The project time, t, starts at year 0 and ends in year n.

An alternative economic indicator, known as IRR, calculates the discount rate when NPV equals zero. The IRR is calculated as

$$IRR = \{iNPV = 0\} \tag{3}$$

If the NPV of an ethylene project is positive or if the IRR is higher than the discount rate, the project is a good investment. Because the two ethylene projects in this paper are similar in investment, a higher NPV, which will lead to a higher IRR, means a better project.

4. Results

4.1. Economic comparison

NPV and IRR of the oil-based ethylene project and the CTO project are show in Table 4. The NPV of the oil-based ethylene project equals 4.46 BRMB and that of the CTO project equals 5.41 BRMB. The NPV of the CTO project is 20.30% higher than that of the oil-based ethylene project. That means the CTO project has a better profitability. This can also be seen from the IRR of the two projects, which is 17.74% for the CTO project and 14.62% for the oil-based ethylene project. Thus, the investment for a CTO project achieves a higher rate of return.

4.2. Cost and revenue components

Fig. 3 shows the cost and benefit of the two types of ethylene projects. It can be seen that the cost and benefit of the oil-based ethylene project is much higher than that of the CTO project. Fig. 4 and Fig. 5 further illustrate the reason of this issue. As shown in Fig. 4 raw material accounts for nearly 80% of the total cost of the oil-based ethylene project. In contrast, raw material accounts for only 27% of the total cost of the CTO project. That's why the cost of the oil-based ethylene is much higher than that of the CTO project. This is consistent with a common sense that the oil-based ethylene project is more sensitive to raw material prices and the CTO project usually needs a large proportion of investment in fixed assets (Xiang et al., 2014a). As for the benefit, it can be seen from Fig. 5 that ethylene and propylene account for 53% of the total benefit of the oil-based ethylene project, yet 81% of the CTO project. The benefit components of the oil-based ethylene project are more diversified.

4.3. Sensitive analysis

4.3.1. Costs and benefits

A sensitive analysis is used to further illustrate what factors matter in this paper. Fig. 6 shows how much the IRR will change when any of the items changes by 1%. As shown in Fig. 6, it can be found that the main product price greatly influences the IRR for

Table 4
Economic indicators of the oil-based ethylene project and the coal-to-olefins project.

	Unit	Oil-based ethylene project	CTO project
NPV	BRMB	4.46	5.41
IRR	%	14.62	17.74

Table 3
Main product composition and price parity.

	Price(RMB/t)	Price parity	Feedstock	
			Naphtha (kt/yr)	Coal (kt/yr)
Ethylene	8420	1.00	1000	300
Propylene	9262	1.10	534	292
Butadiene	15324	1.82	320	78
Light paraffin(C1~C4)	3368	0.40	743	43
Mixtures of C5	4126	0.49	116	–
Crack gasoline	5052	0.60	801	22

Note: Price parity is calculated using historic price data from 2011 to 2015 (Qianzhan, 2016).

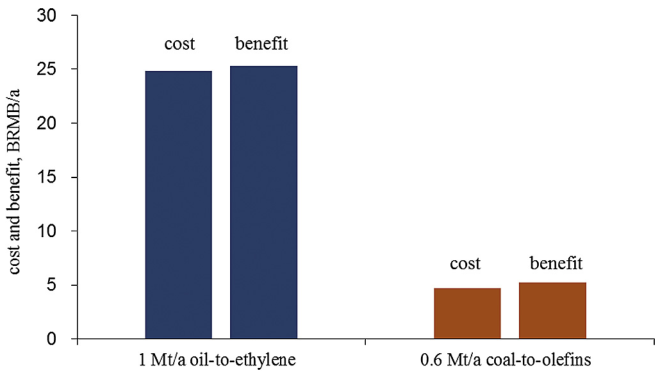

Fig. 3. Cost and benefit of the oil-based ethylene project and the CTO project.

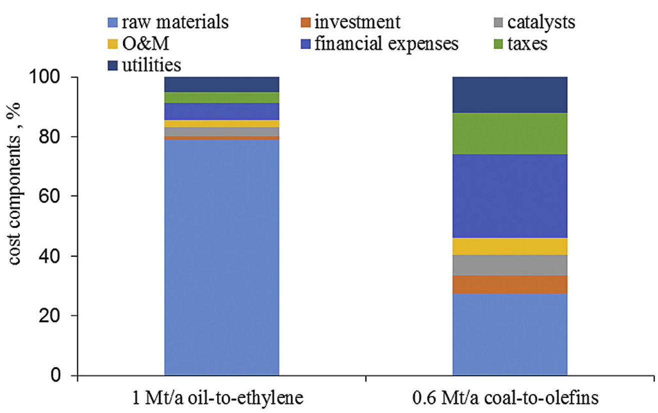

Fig. 4. Benefit components of the oil-based ethylene project and the CTO project.

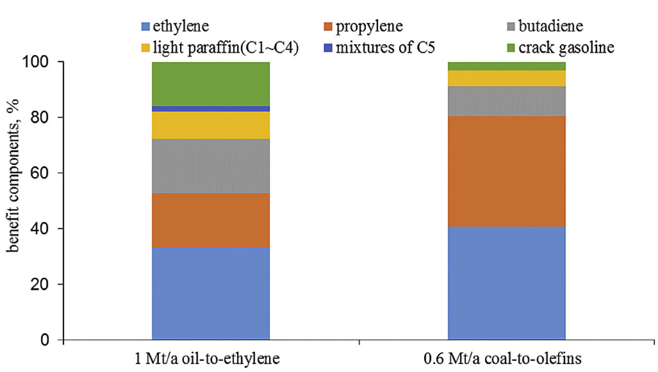

Fig. 5. Cost components of the oil-based ethylene project and the CTO project.

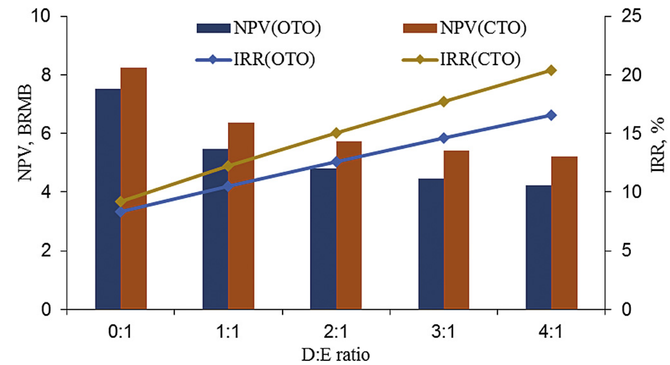

Fig. 7. NPV and IRR of the two projects varying with D:E ratio.

both of the projects. For the oil-based ethylene project, both the raw material (naphtha) price and by-product price have an important influence on IRR. In contrast, the coal price and by-product price have much less influence on the IRR of the CTO project.

4.3.2. D: E ratio

Fig. 7 shows the changes in economic indicators for different D: E ratios. The highest D: E ratio (maximum leverage) offers the highest IRR and the lowest NPV. Comparing with the CTO project, the oil-based ethylene project is more sensitive to D: E ratio in NPV. With the D: E ratio increasing from 0:1 to 4:1, the NPV of the CTO project decreases from 8.25 BRMB to 5.22 BRMB, while that of the oil-based ethylene project decreases from 7.51 BRMB to 4.32 BRMB. However, the difference between the two projects is more evident in IRR. The IRR of the CTO project is much more sensitive to D: E ratio than that of the oil-based ethylene project. With the D: E ratio increasing from 0:1 to 4:1, the IRR of the CTO project increases from 9.25% to 20.36%, while that of the oil-based ethylene project only increases from 8.33% to 16.56%. That is to say, leverage effect is more pronounced for the CTO project than the oil-based ethylene project.

4.3.3. Interest rate

Since the interest rate affect the amount of interest, it has a significant impact on the economic indicators. The economic indicators of the CTO project and the oil-based ethylene project with different interest rates are shown in Fig. 8. It is seen the interest rate has a considerable effect on the two projects. With the interest rate increasing from 3% to 9%, the NPV of the CTO project and the oil-based ethylene project decrease from 7.57 BRMB to 1.11 BRMB and from 8.42 BRMB to 2.12 BRMB, respectively. The IRR of the CTO

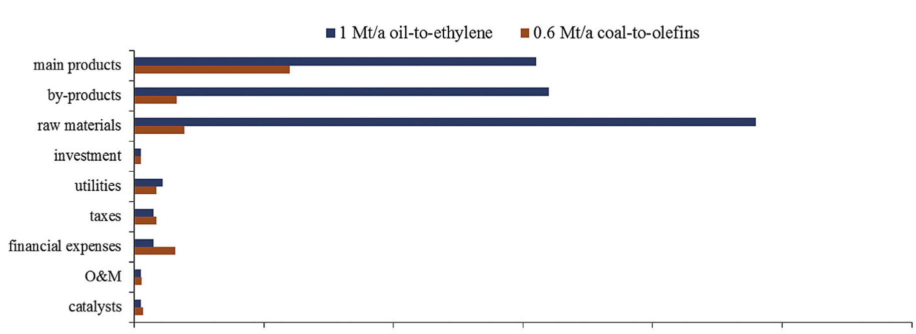

Fig. 6. Sensitive analysis of IRR to different item changes by 1%.

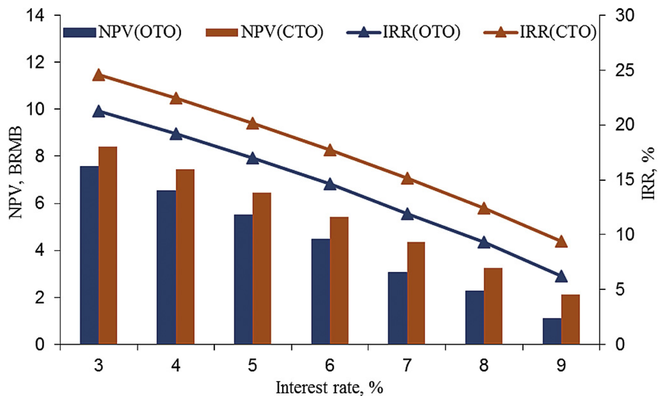

Fig. 8. NPV and IRR of the two projects varying with interest rate.

project and the oil-based ethylene project decrease from 21.29% to 6.25% and from 24.59% to 9.41%, respectively.

4.3.4. Discount rate

The discount rate is another economic parameter that has an effect on NPV but not IRR. NPV of the CTO project and the oil-based ethylene project with different discount rats are obtained and depicted in Fig. 9. It is seen the discount rate has a similar effect on the two projects. With the discount rate increasing from 0 to 10%, the NPV of the CTO project decreases from 8.09 BRMB to 1.83 BRMB, and that of the oil-based ethylene project decreases from 6.94 BRMB to 1.15 BRMB.

5. Discussion

5.1. IRR variation with energy price fluctuations

When the CTO project was widely sought after in China, it was at a time when oil prices were rising. Large coal companies believe that the CTO project is more competitive than the oil-based ethylene project. To study, the economic feasibility in detail with the change in the price of crude oil, it is necessary to carry out further calculations.

5.1.1. Price correlation model

Energy prices are volatile and difficult to predict around the world (Chiroma et al., 2015; Mostafa and El-Masry, 2016; Zhang et al., 2015), but most energy prices and energy products have certain relevance. To make it clear whether the CTO project or oil-based ethylene project is more competitive under different circumstances, this paper connects the energy prices and energy products with simple crude oil prices. A price correlation model is built to answer the question of above what crude oil price is the CTO project more competitive than the oil-based ethylene project. It is hard to obtain long-term historical price data for all of these products, so price correlations between these products are used to calculate IRRs for the two types of ethylene projects from 2003 to 2015.

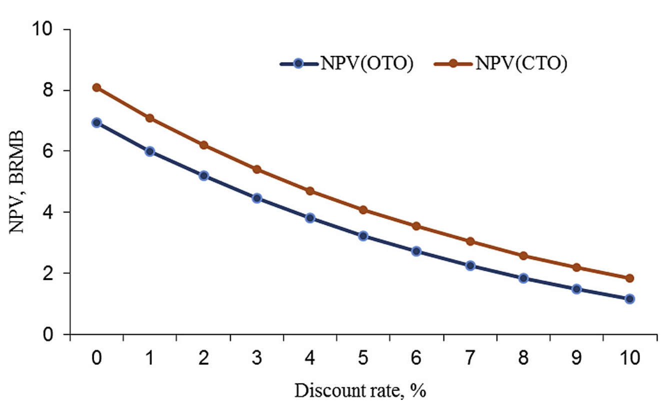

Fig. 9. NPV of the two projects varying with discount rate.

Fig. 10 shows the correlation between the prices of these key energy products. International crude oil prices are considered to have a high correlation with international naphtha prices and a low correlation with coal prices in China. A linear fitting method is used to link the naphtha price and crude oil price shown in Fig. 11. Fig. 12 shows the result of the linear fitting. Because the coefficient of determination (R-squared) is very close to 1 (0.9933), the fitting can be considered reliable. As for energy products, since there is no mature naphtha or ethylene trading market in China, it is better to refer to the price on the international market. Domestic naphtha spot prices (East China average price from Qianzhan Data (Qianzhan, 2016)) were compared with international naphtha spot prices (ARA CIF: Naphtha from Qianzhan Data (Qianzhan, 2016)) from 2010 to 2015. As is shown in Fig. 13, It is found that no matter how the price of naphtha fluctuates, the domestic price of naphtha is approximately 2023 RMB higher than the international naphtha price after being calculated in local currency. This gap is determined by transportation, taxes, reasonable profits and so on. It is hard to obtain long-term public history data of the domestic prices of naphtha, so this price gap is used to infer the prices of naphtha in other years. As for ethylene prices, considering the market location, the CFR Northeast Asia ethylene prices are treated as the domestic ethylene prices when calculating (shown in Fig. 14).

5.1.2. Fluctuant IRR of the CTO project

After taking annual data into consideration, we can obtain the results shown in Fig. 15 and Fig. 16. It can be clearly seen that the IRR of both projects rise when the crude oil price rises because the downstream product prices rise together. This can be attributed to a better economy leading to a better market. It can be found that the IRR of the CTO project rises much more rapidly than that of the oil-based project. On one hand, this rise is because coal prices change less than crude oil or naphtha, which makes the CTO project less sensitive to raw material prices. On the other hand, ethylene prices are highly connected to naphtha prices, but not to coal prices. The simultaneous rise in prices of ethylene and naphtha makes the profit stay at a more reasonable level. For the CTO project, the rise in product prices dominates the profit.

First, it seems that the crude oil price of $65/bbl is a dividing crest. In most years, when crude oil prices are below $65/bbl, the IRRs of the CTO project are less than those of the oil-based ethylene project. If the oil prices are higher than $65/bbl, the opposite is true. In 2003, 2004 when crude oil prices were low, the IRRs of the oil-based ethylene project were still higher than 13%. In comparison, the IRRs of the CTO project were barely above 0, which means the CTO project can almost be considered a loss. When crude oil prices quickly rose to $110/bbl from $55/bbl, which occurred from 2005 to 2008, the IRRs of the CTO project quickly exceeded those of the oil-based ethylene project. The gap between the IRRs of the CTO project and the oil-based ethylene project then expanded rapidly. In 2007, this gap reached a maximum at 4%. Oil prices then fell sharply in the 2008 economic crisis, which caused a sharp drop in the prices of ethylene and by-products. Obviously, the price of coal did not drop as much as the prices of these products. The IRRs of the CTO project quickly fell below zero in 2009 and 2010. Interestingly, even if the price of oil rose in 2010, the loss of the CTO project is even more serious than in 2009.

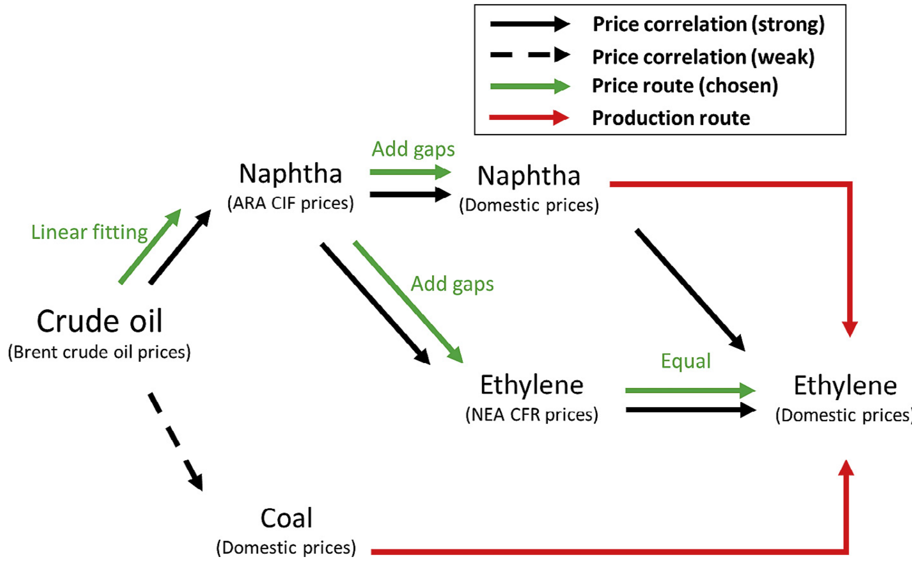

Fig. 10. Correlation between energy products.

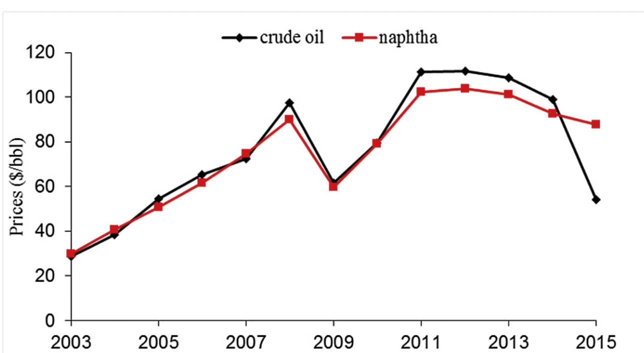

Fig. 11. Historical data of crude oil and naphtha prices.

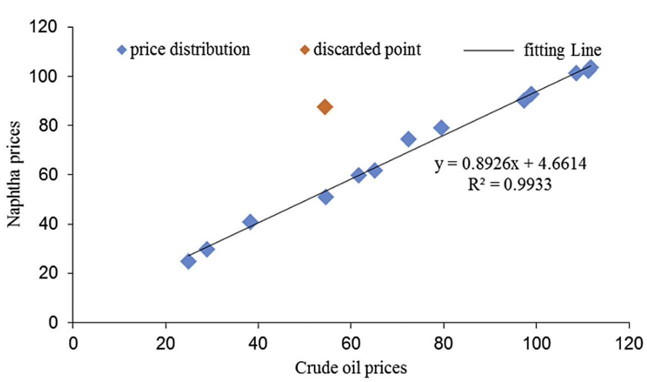

Fig. 12. Linear fitting of crude oil and naphtha prices.

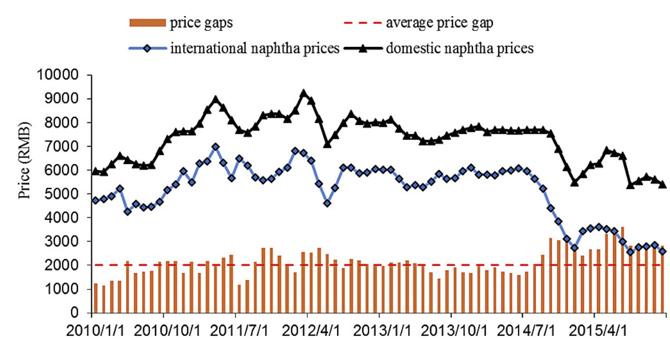

Fig. 13. Price gaps between international naphtha prices and domestic naphtha prices.

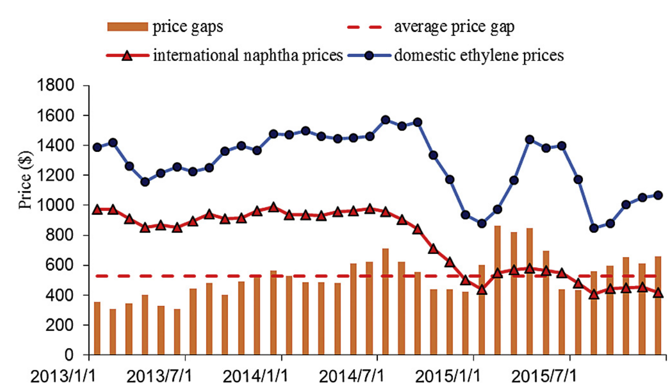

Fig. 14. Price gaps between international naphtha prices and domestic ethylene prices.

This loss may be caused by the "4 trillion government investment plan," which was launched by the Chinese government. The plan has a strong stimulating effect on the economy, which has led to a sharp rise in coal prices. Oil prices then rose again from 2011 to 2014, more sharply than ever. Though the IRRs of the oil-based ethylene rose a little, the CTO project benefitted a lot from the high oil prices. The IRR of the CTO project reached as high as 40% in 2014, which was more than twice the IRR of the oil-based ethylene project. Unfortunately, good times do not last long. The collapse in oil prices in 2015 poured really cold water on the CTO project. The CTO project seriously lost again, similar to what happened in 2009.

We have reached a conclusion that in recent years, the outbreak of the CTO projects in China has a reason. During the periods of high crude oil prices, such as 2011–2014, the CTO project does have a great advantage over the oil-based ethylene project. However, when oil prices fall sharply, the CTO project's losses will be very serious. Due to substantial correlation of the prices of oil and

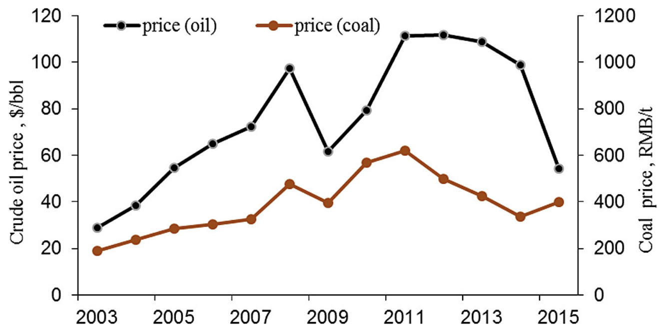

Fig. 15. Historical data of crude oil and coal prices.

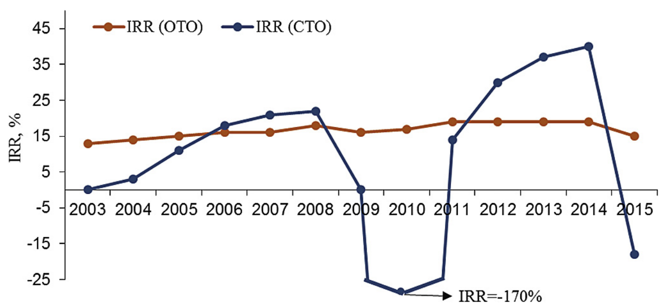

Fig. 16. IRRs of the oil-based ethylene and the CTO projects in recent years.

petrochemical products while international oil prices and domestic coal prices are substantially decoupled, the CTO project has less anti-risk ability to the international oil market fluctuation than the oil-based ethylene project. For the Chinese government, too many CTO projects will also bring higher systemic risk. It will be a good choice for CTO enterprises to extend the industry chain, develop high-value-added polyester products and other fine chemical products.

5.2. Environmental policy impact

When talking about the coal chemical industry, it is inevitable to think about the huge carbon emissions and wastewater discharge. With China's restrictions on carbon emissions (Shao et al., 2016) and the emphasis on environmental protection (Jalil and Mahmud, 2009), it is unlikely that coal chemical enterprises could operate with the current environmental costs in the future. Under these circumstances, it is important to study whether the CTO project is still attractive compared to the oil-based ethylene project.

To limit carbon emissions, carbon tax and carbon trading are two commonly used methods around the world (Chiu et al., 2015). In view of China's current situation (Xiong et al., 2017), carbon trading is more likely to be implemented. The Chinese government has set a goal of reducing carbon emissions by 60%–65% by 2030 compared to 2005. That is the basis for carbon trading of the two types of projects. To achieve the intended target, these two types of enterprises must reduce carbon dioxide emissions by 3% per year compared to the present emissions. Assuming at the same time, these two types of enterprises will purchase the emission rights instead of reducing emissions through technological progress. As for wastewater, a surcharge to the current cost of the wastewater treatment is added. Because naphtha is a very clean raw chemical material, the oil-based ethylene project does not need to pay too much surcharge for the wastewater. Table 5 shows the current carbon emissions, wastewater discharge and their costs and the

Table 5
Carbon emission trading costs and wastewater surcharge.

	Oil-based ethylene project	CTO project
Carbon emission (t/tolefin)	2.00[a]	10.04[b]
Carbon emission trading	46%[c]	46%[c]
Trading price (RMB/t)	50	50
Time required	15 yrs[d]	15 yrs[d]
Wastewater emission (Mt/yr)	–	27
Wastewater surcharge (RMB/t)	–	10
Time required	–	10 yrs[e]

Note:
[a] The data is based on Chen's work (Chen et al., 2017).
[b] The data is based on Wu's work (Wu, 2014).
[c] China's CO_2 emissions per unit of GDP fell 28.56% by 2013 compared to 2005. That number reached 35% by 2015 and it will reach 65% by 2030 when the ethylene projects end. That means these two types of ethylene projects will cut CO_2 emissions by 46% compared to current emissions.
[d] It is a gradual process to cut CO_2 emissions, and it takes 15 years to achieve. A linear method is used to calculate the CO_2 emissions reduction.
[e] The calculation process is similar to the CO_2 emissions reduction. Because the water pollution problem is more urgent than carbon emissions, the time required is 10 years.

assumptions added. According to relevant literature (Li et al., 2017; Li and Lu, 2015; Zhao et al., 2016), the average carbon transaction price of 50 RMB/tCO_2 can be reasonable. China's CO_2 emissions per unit of GDP fell 28.56% by 2013 compared to 2005. That number reached 35% by 2015 and it will reach 65% by 2030 when the ethylene projects end. That means these two types of ethylene projects will cut CO_2 emissions by 46% compared to current emissions. A linear growth method is used to calculate the CO_2 emissions reduction. That means each project will trade 3% more CO_2 every year from production. Take the CTO project for example, 3% of total CO_2 emissions will be trade in the first year and trading price is 50 RMB/tCO_2. That will cost 9.04 MRMB. That number will be 18.08 MRMB in the second year and finally come to 135.54 MRMB in year 15.

Some coal chemical enterprises in China choose to discharge wastewater to an evaporation pond but with no further treatment. This is actually not a proper way to deal with wastewater. Strictly speaking, such enterprises did not meet the corresponding emission standards. This situation is not uncommon in China. This is one of the most important reasons why many experts oppose fast development of coal chemical industry. Technically, wastewater can be treated to meet emission standards. The key to the problem is how much it costs. This is why this paper takes an economic approach to assess the wastewater discharge. Because of the complexity of the coal chemical industry wastewater treatment, the surcharge will come to at least 10 RMB/t. Similar to carbon trading cost, a linear growth method is adopted. The wastewater surcharge will cost 27 MRMB in the first year and 270 MRMB in year 10. The wastewater surcharge of the oil-based ethylene project can be omitted because of its small amount of wastewater discharge and low pollution.

Fig. 17 shows the economic indicators gaps between the CTO project and the oil-based ethylene project. Raw material and product prices are still consistent with the basic scenario when the crude oil price is approximately $70/bbl. The results show that both the carbon trading costs and the wastewater surcharge have a negative influence on the IRR of the CTO project. IRR equals the discount rate which makes NPV 0. Carbon trading and wastewater surcharge cause 1.34% and 4.48% decline in the IRR of the CTO project, respectively. Carbon trading costs only cause a 0.51% decline in the IRR of the oil-based ethylene project. The IRR of the CTO project is 3.12% higher than the IRR of the oil-based ethylene project when carbon trading costs and wastewater surcharge are

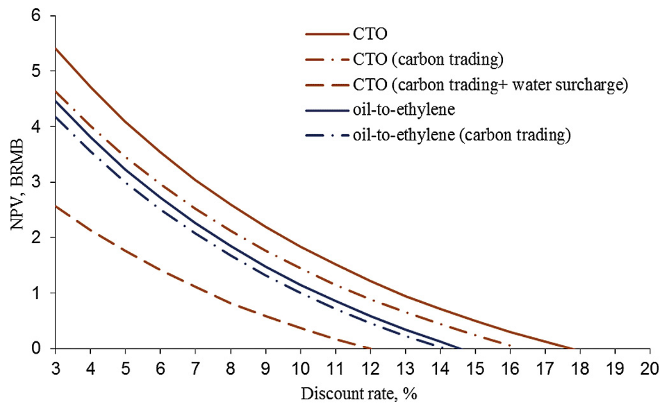

Fig. 17. NPV influenced by carbon emission trading costs and wastewater surcharge.

not taken into account. However, with these two costs calculated, the IRR of the CTO project is 2.19% less than the IRR of the oil-based ethylene project, which means that the CTO project no longer has an advantage over the oil-based ethylene project.

The negative impact of strict environmental policy on CTO profitability can also be seen from the NPV. With discount rate maintaining 3%, carbon trading and wastewater surcharge are calculated in sequence. The NPV of the CTO project first decreases from 5.41 BRMB to 4.63 BRMB, then decreases from 4.63 BRMB to 2.57 BRMB. In contrast, carbon trading costs only 0.29 BRMB decline in the NPV of the oil-based ethylene project.

The Chinese government has decided to increase the environmental governance. This is definitely not just a talk. For the first time, ecological progress was discussed in the form of a single article in the 18th National Congress of the Communist Party of China. This deeply reflects that the government attaches great importance to the ecological environment of China. The CTO project will therefore be negatively affected, which is not surprising. For a CTO project, cleaner and cheaper wastewater treatment processes are suggested. Recent years, the phenol and ammonia recovery process has been continuously improved in economic performance (Cui et al., 2017). The innovation of for CGW treatment provides favorable conditions for the application of biological treatment (Wang et al., 2011). Advanced treatment process is also developing very fast (Hou et al., 2015; Zhuang et al., 2015).

6. Conclusion

With a rapidly developing economy, the consumption of ethylene in China is increasing continuously. However, domestic oil production has been shown to have peaked or to be on the verge of peaking, which seems hard to support the growth of ethylene consumption. In contrast, coal accounts for about 63.7% of China's energy consumption, making it far more important than other energy resources. Even if half of the domestic ethylene is produced from coal, there are only 3.8% of the domestic coal production consumed. Because of the increasing coal supply and rising crude oil prices from 2004 to 2014, enterprises in China are trying to replace oil with coal to produce petrochemical products. The CTO project is one of the typical projects. This paper carries on detailed calculations for the economic feasibility of the oil-based ethylene project and the CTO project. The results show that when international crude oil prices are high (above $65/bbl), the CTO project has advantages over the oil-based ethylene project, except in 2010, when China's coal prices were rising fast because of the large government stimulus package. It is especially notable when oil prices are more than $100/bbl and the IRR of the CTO project is nearly 40%, approximately twice the IRR of the oil-based ethylene project. When oil prices are low (below $65/bbl), the IRRs of the oil-based ethylene project still remain above 10%, while the CTO project is barely profitable. During 2009, 2015, when oil prices fell sharply, the IRRs of the CTO project were below zero, which shows that oil prices have a greater impact on the CTO project than the oil-based ethylene project. Thus, the CTO project has less anti-risk ability to the international oil market fluctuation than the oil-based ethylene project, due to substantial correlation of the prices of oil and petrochemical products while international oil prices and domestic coal prices are substantially decoupled.

When taking the cost of carbon emission reduction and wastewater surcharge into account, the economic feasibility of the CTO project is weakened further. Both the carbon trading costs and the wastewater surcharge have a negative influence on the IRR of the CTO project. This is because the CTO project is environmentally unfriendly. Given carbon trading price and wastewater surcharge equaling 50RMB/t and 10 RMB/t respectively, 1.34% and 4.48% decline are brought to the IRR of the CTO project. In contrast, only 0.51% decline is brought to the IRR of the oil-based ethylene project. On the other side, the NPV of the CTO project first decreases from 5.41 BRMB to 4.63 BRMB, then decreases from 4.63 BRMB to 2.57 BRMB because of the carbon trading and wastewater surcharge. Only 0.29 BRMB decline is caused in the NPV of the oil-based ethylene project. The impact of wastewater surcharge and carbon emission costs on CTO project is far larger than that on oil-based ethylene projects. Taking all these environmental policy impact into calculations, the IRR of the CTO project is 2.19% less than the IRR of the oil-based ethylene project, which means that the CTO project no longer has an advantage over the oil-based ethylene project. Since the national environmental policy is tightening, the CTO project is predicted to be less competitive.

In conclusion, the CTO project is not suitable for large-scale development due to the unpredictable international oil market, unstable profit and possible environmental impact. But for some special regions, which is lack of oil refinery but coal is plenty and cheap, it is still possible to build some CTO projects properly. It is also possible for some enterprises to produce olefin from cheap methanol which comes from by-product utilization of other processes. It may be a good choice to improve the competitiveness of the CTO project by extending the industry chain, producing high-value-added products such as polyethylene, ethylene oxide and so on. It's also a necessary path to develop circular economy. Studies have shown that the coal gasification based co-production system has higher energy efficiency and less capital expenditure than traditional single production systems (Yang et al., 2012; Zhang et al., 2014). The coal mining waste can be converted into wealth and play more and more important roles in many fields (Haibin and Zhenling, 2010; Oliveira et al., 2016). We hope that Chinese government and investors will be more cautious to invest in the CTO project. For those who have invested or will invest in a CTO project, developing cleaner and cheaper wastewater treatment processes is suggested.

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