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Carbon reduction potential and cost evaluation of different mitigation approaches in China's coal to olefin Industry

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ABSTRACT

Coal-based olefin (CTO) industry as a complement of traditional petrochemical industry plays vital role in China's national economic development. However, high CO_2 emission in CTO industry is one of the fatal problems to hinder its development. In this work, the carbon emission and mitigation potentials by different reduction pathways are evaluated. The economic cost is analyzed and compared as well. According to the industry development plan, the carbon emissions from China's CTO industry will attain 189.43 million ton CO_2 ($MtCO_2$) and 314.11 $MtCO_2$ in 2020 and 2030, respectively. With the advanced technology level, the maximal carbon mitigation potential could be attained to 15.3% and 21.9% in 2020 and 2030. If the other optional mitigation ways are combined together, the carbon emission could further reduce to some extent. In general, the order of mitigation potential is followed as: feedstock alteration by natural gas > CO_2 hydrogenation with renewable electricity applied > CCS technology. The mitigation cost analysis indicates that on the basis of 2015 situation, the economic penalty for feedstock alteration is the lowest, ranged between 186 and 451 CNY/tCO_2, and the cost from CCS technology is ranged between 404 and 562 CNY/tCO_2, which is acceptable if the CO_2 enhanced oil recovery and carbon tax are considered. However, for the CO_2 hydrogenation technology, the cost is extremely high and there is almost no application possibility at present.

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1. Introduction

Olefins (ethylene, propylene, butadiene and butylene) are the primary building blocks for various chemical intermediates, polymers and rubbers, which are critical to the development of national economy (Qu, 2012). As a result of the rapid economic development, the olefins demand is soaring in China. For example, the ethylene demand significantly increased from 18.42 million ton (Mt) to 45.30 Mt during 2005–2015 and the propylene demand increased from 13.75 Mt to 33.67 Mt (Qian, 2013; Zhuochuang Information, 2016). However, the self-sufficiency rates of ethylene and propylene in China are steadily maintained around 50% and 70% respectively, indicating that there is still a large gap between the domestic supply and demand.

Currently, China's olefins production is mainly produced from oil-to-olefins (OTO) route, which is excessively dependent on oil imports. Considering the energy security, it is in urgently need to seek other alternative production routes. It is well known that olefins could also be produced from coal- and gas-derived technological routes, such as coal-to-olefins (CTO), nartural gas-to-olefins (NGTO), coke oven gas-to-olefins (COGTO), methanol-to-olefins (MTO) and steam cracking of light alkanes, etc. Due to the unique characteristics of China's resource endowment of 'more coal, less oil, and poor gas', it is essential to develop CTO industry in China. Since the first CTO project in Datang Duolun put into production in 2010, 15 CTO projects have been set up by 2015. In China's "13th Five Years" plan, it is explicitly mentioned that CTO industry as a complement of traditional petrochemical industry will be promoted (National Energy Bureau, 2017). More than 6.03 Mt ethylene production will come from the CTO route in China and the proportion will be attained to 18.5% of total by 2020, which is an obvious increase compared to 7.3% in 2014 (China Industry Information, 2017a,b,c). Therefore, it is foreseeable that CTO industry will play more and more important role in China's national economic development.

However, at present, CTO industry also faces several drawbacks to hinder its large-scale development, such as low energy efficiency, high CO_2 emission, and high water consumption. Given the potential importance of CTO industry in China, considerable works have been done with the focus on the techno-economic evaluation based on process simulation. For example, Xiang et al. (Xiang et al., 2014a,b; Xiang et al., 2015a,b) made a comprehensive techno-economic analysis of the CTO process and compared with OTO, NGTO, COGTO and MTO processes. It was found that the coal-based olefins process showed prominent advantage in product cost because of the low price of its feedstock. However, it suffered from the limitations of higher capital investment, lower energy efficiency, and higher carbon emissions. While, between the coal-based olefin production processes, the CTO route possessed better techno-economic performance than coal based Fischer-Tropsch to olefins (CFTO) route (Xiang et al., 2016). Besides, Xiang et al. also conducted a detailed techno-economic analysis of the CTO process with CO_2 capture and storage (CCS) technology (Xiang et al., 2014a,b). It was revealed that the CTO process with CCS was more competitive in product cost and more capable of resisting to market risk if compared with MTO process, indicating CTO process with an appropriate CO_2 reduction was more applicable into China's olefins industry. Man et al. (Man et al., 2014) designed a coke-oven gas assisted CTO process. In the co-feed process, the energy efficiency was increased by 10% and the life cycle carbon footprint was reduced by around 85% in comparison to the conventional CTO process. Yang et al. (Yang et al., 2013) also proposed a new natural gas assisted CTO process integrating CO_2 recovery gasification or CH_4/CO_2 reforming techniques. Similarly, the carbon efficiency and the energy efficiency were increased with CO_2 emission reduced to some extent. Ye et al. (Ye et al., 2018) conducted a life cycle assessment to determine whether the application of oil field gas could relief the problems of high consumption and pollution in CTO system. Their results showed that oil field gas-assistance in CTO process could decrease the potential impact on climate change, carcinogens, and fossil depletion. Thus, the oil field gas-assistance could be recommended as an attainable and effective means of carbon reduction in China's CTO industry. Yu et al. (Yu et al., 2017) evaluated the economic and CO_2 reduction benefits of a CTO plant using a CO_2 enhanced coalbed methane process and fuel substitution by extracted methane. Zhou et al. (Zhou et al., 2015) introduced the concept of energetic penalty and economic penalty for closing the CO_2 loop of CTO projects in China. It was found that there were great differences in penalties between different regions.

To the best of our knowledge, most of the previous works related CTO system were mainly focused on the techno-economic assessment, taking the energy efficiency, GHG emission and the cost as the analysis indicators. In fact, it is not enough to study the carbon emission of a certain technology from the process level. It is more meaningful to reveal the carbon emission and its reduction potential from industry perspective by comprehensively combining the industry scale and future planning. However, the understanding of carbon emission in CTO industry from the industry perspective is rarely reported. There are still many open questions not answered. Therefore, the main purpose of this paper is to analyse and reveal the carbon emission in China's CTO industry. Besides the status quo analysis, the mitigation potentials under different development scenarios in China's CTO industry are presented as well. Furthermore, the reduction cost analysis is also made to reveal the economic penalty of different mitigation technologies. We believe that the results could provide sufficient insights for the future industry development and give suggestions for policymakers. In addition, the CTO industry as a typical emerging coal chemical industry, the investigation on its carbon emission reduction will act as reference for the other similar carbon-intensive coal chemical industries.

2. Methodology and data sources

2.1. Calculation model of CO_2 emission

As shown in Eq. (1), the CO_2 emission is calculated by the emission factor method, which is the activity level (A) multiplied by the emission factor (EF) value. The A_j is denoted as the olefin production from j process in CTO industry and the EF_j value is the carbon footprint if 1 ton olefins produced in specific j process.

$$E = \sum_j A_j \times EF_j \quad (1)$$

2.2. Scenario setting for carbon mitigation

2.2.1. Potential choice of mitigation pathways

Technology improvement: the energy consumption of CTO technology is two times as high as that of traditional petrochemical route as a result of the long production process (Xiang et al., 2016). As an emerging industry, most CTO plants are established in small-scale and their technology development is not mature enough. Therefore, large improvement space for energy efficiency is existed. To improve the energy efficiency, actions could be taken at different levels. At the enterprise level, system integration and optimization is a feasible way. For the entire industry level, the closure of outdated small-scale plants and establishment of new large-scale plants with updated technology is the most efficient way.

Feedstock alteration: in CTO system, syngas with low H/C ratio ranged between 0.5 and 1.0 is generally formed in the gasification process, thereby the water gas transformation is needed to adjust the H/C ratio, accompanying with a great amounts of CO_2 formation. However, if taking natural gas as the raw material, syngas with high H/C ratio (~2) is produced by wet reforming process with little CO_2 formed (Xiang et al., 2016). Therefore, the olefin production derived from natural gas (called NGTO route for short) is a more low-carbon route. China, as the nation with the largest shale gas reserves in the worldwide, has formulated ambitious plan for its development, such as Shale Gas Development Planning (2016–2020), in which it is proposed that the shale gas industry will be sharply accelerated during the “14th Five Year Plan” and “15th Five Year Plan” periods. The shale gas production will attain to 30 billion cubic meters (bcm) in 2020 and 800-1000 bcm in 2030 (Lassagne et al., 2013; Han, 2005; US Energy Information Administration, 2011). It is predicted that the proportion of natural gas to primary energy consumption will be higher than 10% by 2020 in China. Therefore, the NGTO route will be possibly boosted with the shale gas development in the future, though it is not encouraged at present.

CCS technology incorporation: CCS technology as an end-control technology for the formed CO_2, is generally recognized as a feasible solution to curb the global warming in a brief period (General Office, 2014). As an emerging technology with plenty of uncertainties, great research has been done relevant to technology and energy efficiency improvement, economic evaluation and practical feasibility (Choi et al., 2009; Zendehboudi et al., 2012; Zendehboudi et al., 2013; National Energy Administration, 2016; Jin et al., 2017; Wang et al., 2017; Jin et al., 2017). Diego et al. reported that the CCS cost is obviously low in the high purity CO_2 sources (Diego et al., 2017). Therefore, high concentrated CO_2, mainly from gasification derived-coal chemistry industry, is the priority for the CCS application. It is known, in CTO industry, CO_2 emission is mainly from two sources: (1) ~60% CO_2 is emitted from the purification process with high concentration (~85%) and high pressure (generally 3–5 MPa); (2) the rest 36% CO_2 is emitted from the boiler with low concentration (10–15%) and atmospheric pressure (Amore and Bezzo, 2017). Therefore, CTO industry presents high potential for the CCS technology incorporation. As reported, the first CCS pilot project in Shenhua company has been operated for nearly 3 years with an annual injection of 100,000 ton CO_2 (Dahowski et al., 2012). Therefore, CCS technology is going on its application road.

Application of CO_2 hydrogenation technology: besides CCS technology, the captured CO_2 could be converted into high value-added chemicals. One of the most popular product is methanol, which is largely used in chemical and energy-related application. Compared to the synthesis strategies of biochemistry, electrochemistry, and photochemistry, methanol synthesized from a mixture of H_2/CO_2 via thermochemistry is supposed to be the most realistic way. Nowadays, several pilot projects are established in the worldwide and the single tube experiment has already started in China, indicating its potential application in the near future (Cai et al., 2018). In this process, the hydrogen is supposed to be generated by water electrolysis technology (Bellotti et al., 2017).

Other mitigation technologies: biomass to olefins is considered to be an ideal route from circular economy perspective. To date, there are two technical routes (Nguyen et al., 2017). The first one is composed of chemicals production of biomass pre-treatment, gasification, methanol synthesis and olefin production. The other one is synthesized by taking ethanol as intermediate. As far as we known, the biomass-derived routes is still under experimental stage, which is impossible to realize the industrial application in a short term.

Therefore, based on the above discussion, according to technology maturity and compatibility with existing CTO process, we select technology improvement, feedstock alteration, CCS control technology and CO_2 hydrogenation by thermochemistry as the potential choices for CO_2 mitigation in CTO industry, which is clearly presented in Fig. 1. Among them, system technology upgrading is a certain way, and the others are possible ways in the near future.

2.2.2. Scenario setting for carbon mitigation

To predict the carbon mitigation potential in CTO industry, three scenarios are designed. Business-as-usual scenario: the technology keeps constant as 2015 average level and no mitigation technology is matched. The realistic scenario: the technology level is inevitably improved as planned, as a result, the carbon emission will be partly reduced. In this scenario, three situations with different development levels (2015, 2020 and 2030 advanced level) are set according to the industry plans. The ideal scenario: one of the optional technologies, such as feedstock alteration, CCS control technology and CO_2 hydrogenation by thermochemistry, combined with technology improvement, is contributed to the carbon reduction in common. It should be noted that in the ideal scenario, the technology improvement is attained to the 2020 advanced level in 2020 and 2030 advanced level in 2030. The emerging

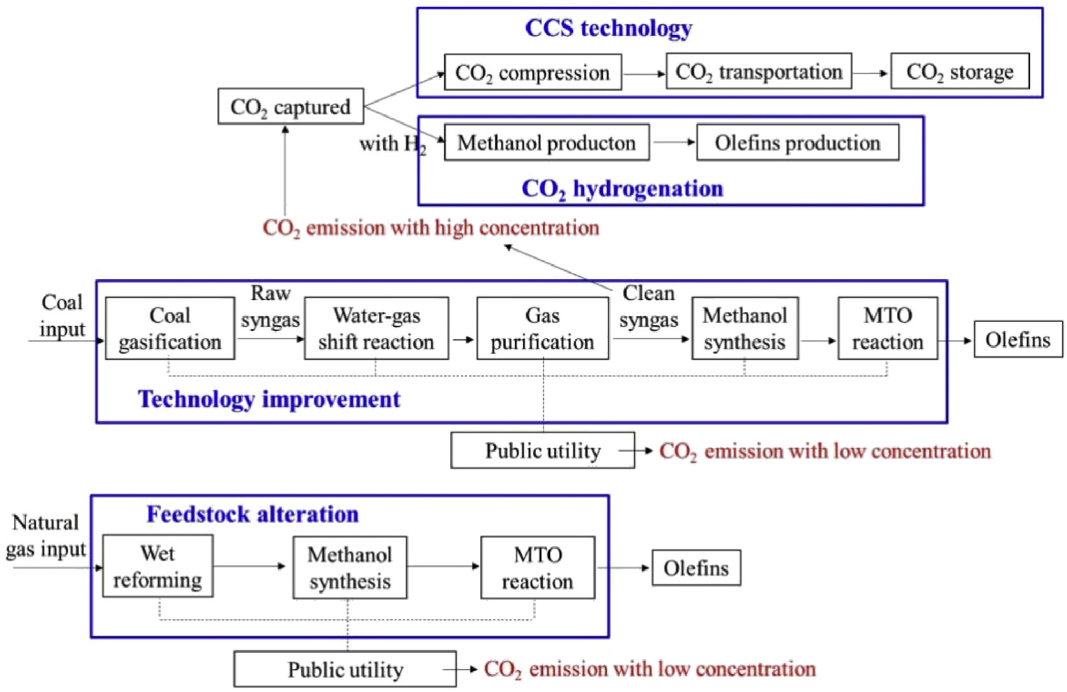

Fig. 1 – The explanation of different mitigation pathways in CTO industry.

technologies is only applied during 2020–2030 and the permeability is fixed at 20% in 2030.

2.3. *Calculation method of mitigation penalty*

2.3.1. *The calculation model of mitigation cost*

The CO_2 mitigation cost (MC) is a direct indicator to compare the economic penalty (Shi et al., 2018), which represents the difference of cost per ton of CO_2 emissions avoided with and without reduction technologies. The calculation model is generally expressed as Eq. (2).

$$MC = \frac{PC_{MT} - PC_{ORI}}{EF_{ORI} - EF_{MT}} \tag{2}$$

where PC refers to the cost per ton olefins product and EF is the emission factor value in CTO industry. The subscripts $_{MT}$ and $_{ORI}$ are referred to the industry configured with and without CO_2 mitigation technologies, respectively.

2.3.2. *Product cost calculation model*

As mentioned in Eq. (2), to implement MC calculation, the product cost per ton olefins product is a necessary parameter. According to the literature (Xiang, 2016), the product cost could be calculated by the product factor estimation method, as shown in Eq. (3).

$$PC = C_R + C_U + C_{O\&M} + C_D + C_L + C_M + C_A + C_{DS} \tag{3}$$

where PC is the product cost per ton olefin product, C_R is the raw material cost, C_U is the utilities cost, $C_{O\&M}$ is the operating & maintenance cost, C_D is the depreciation cost, C_L is the labor operating cost, C_M is the management cost, C_A is the administrative cost, C_{DS} is the distribution and selling cost.

2.4. *Data sources*

For the data of industry development, the olefins production is from the theoretical production capacity multiplied by 80% operating rate, which is reported by industry information (Industry Information, 2015). The specific energy efficiency values at different development periods in CTO are obtained from the industry plans released by National Department of Energy (Energy efficiency, 2012; National Development, 2017).

The carbon footprint in different process is calculated by the lifecycle analysis. The detailed data of material flow and energy flow about raw material, energy input and products, gas emission in different processes are collected from the literature reports. For example, the data for the conventional CTO, NGTO processes are obtained from Xiang et al. work (Xiang et al., 2014a,b). For the CTO + CCS process, the extra data of energy consumption and gas emission in the CCS part is also cited from Xiang et al. work (Xiang, 2016). For CTO + CO_2 hydrogenation process, the extra data for CO_2 hydrogenation process are collected from Bellotti et al. work (Xiang et al., 2014a,b; Bellotti et al., 2017). In combination with the GHG emission of raw material production process (Xiang et al., 2015a,b; Gabi education 6.0 software), the lifecycle carbon footprint under specific process could be roughly calculated. The detailed information is seen in Supporting Information.

For the necessary economic parameters, the prices of raw materials and utilities are based on the average prices of 2015 in China (Current Natural Gas Classification Price Statistics for Major Cities in China, 2015; China Industry Information, 2017a,b,c). Operating labor cost is estimated according to the project capacity (Zhao et al., 2018). The capital investments which is involved in the product cost as the form of

Table 1 – Assumption for the estimation of product cost in CTO industry.

Components	Basis
Raw materials	Coal price 400 CNY/ton; natural gas price 3.3 CNY/m^3;
Utilities	Water price 3.5 CNY/ton; electricity 0.7 CNY/kwh; steam 42 CNY/GJ
Operating and maintenance	2% of fixed capital investment
Laborers operating cost	CTO 300 labors, 70,000 CNY/labor/year
Depreciation	Life period 20 years, salvage value 4%
Management cost	10% of labor cost, operating and maintenance
Administrative cost	2% of product cost
Distribution and sell cost	2% of product cost

depreciation cost, are directly obtained from the literature report. For example, the data of capital investment of CTO process is from Xiang et al. work and the data of CO_2 hydrogenation to methanol is from Bellotti et al. work (Xiang et al., 2014a,b; Bellotti et al., 2017). The rest parts of product cost are roughly calculated according to the specific ratio, as shown in Table 1 (Xiang, 2016). For the estimation of CCS cost, it is mainly referred to the Shenhua CCS pilot project in China (Wu, 2014; Zhang et al., 2016). In addition, other factors, such as the captured cost and the transportation cost are also considered (Xiang, 2016; Dahowski et al., 2012).

3. Results and discussion

3.1. *The current status of China's CTO industry*

As shown in Fig. 2, the current CTO projects are mainly located in Inner Mongolia, Shanxi, Shannxi, Gansu and other provinces, which are close to the coal storage sites. Up until 2015, there are 15 CTO projects built and put into production in China, for which the total production capacity is 8.22 Mt. Besides, additional 23 CTO projects are under construction and probably will be established before 2020. The total production capacity will be attained to 23.87 Mt by then. In addition, more than 21 CTO projects are planned in the near future and the theoretical total production capacity will be 15.71 Mt. It is believed that these projects will quickly start up if the national policy allows. Supposing that the construction period of CTO projects is about 10 years, the total CTO production capacity will be ~39.58 Mt by 2030, which will be nearly five times of current capacity. Therefore, it is foreseeable that CO_2 emission from CTO industry will undergo sharply increase as a result of its large-scale development.

As shown in Fig. 3, the historic carbon emission is estimated on the basis of the lifecycle carbon footprint in Table 2. The carbon emission in 2010 is only 3.65 $MtCO_2$, while in 2015, it is obviously increased to 65.23 $MtCO_2$. The carbon emission in 2015 is almost 18 times of that in 2010. Among these emissions, 90% carbon emission is discharged from the plant itself and the rest 10% is associated with indirect emission from the upstream stage, such as coal mining and washing. For the emission happened in the plant, 58% is mainly from the production process and the rest 42% is from the energy combustion in public utility.

3.2. *The carbon mitigation potential in China's CTO industry*

As shown in Fig. 4, under the business-as-usual scenario, up to 2020, the carbon emission will significantly increase to 189.43 $MtCO_2$ if the constructed CTO projects all put into production. Furthermore, if the planned CTO projects all put into operation in 2030, the carbon emission will be 314.11 $MtCO_2$. This result is extremely shocking, which is close to the total carbon emission from the current coal chemical industry

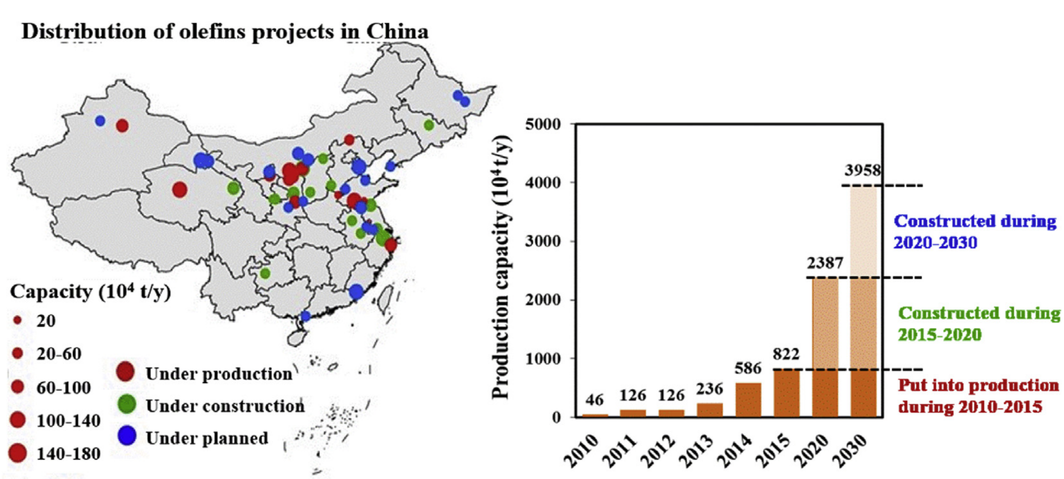

Fig. 2 – The development tendency of production capacity in China's CTO industry.

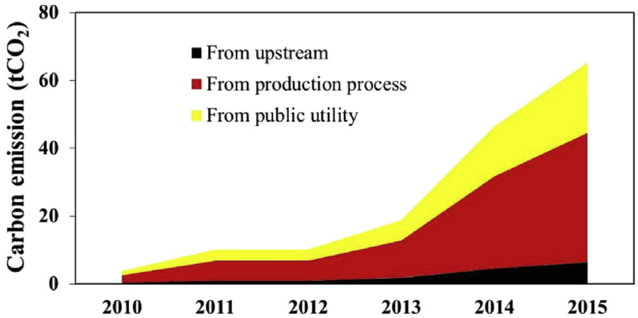

Fig. 3 – The current carbon emission from China's CTO industry.

(Zhang et al., 2019). Apparently, if the CTO industry is developed in large scale without any technology improvement, its carbon emission will make significant influence.

Under the realistic scenario, if the energy efficiency is improved as planned, the carbon emission will be certainly reduced accordingly. The EF values under different technological levels could be roughly estimated from the energy consumption data (Zhou et al., 2010), which are listed in Table 2. The carbon mitigation potentials through technology upgrade are shown in Fig. 4. It is seen that if the energy consumption attains the 2015 advanced level, the carbon emission will be 173.58 $MtCO_2$ in 2020 and 287.83 $MtCO_2$ in 2030, with 8.3% mitigation potential. Under the 2020 advanced level, the carbon emission will reduced to 160.41 $MtCO_2$ in 2020 and 265.98 $MtCO_2$ in 2030, with 15.3% mitigation potential. Furthermore, if the energy consumption attains the 2030 advanced level, the carbon emission in 2030 may decrease to 245.40 $MtCO_2$, achieving a maximal reduction rate of 21.9%. Therefore, it seems that the improvement of energy efficiency by the upgrade of technology level is an effective way to reduce the carbon emission.

Under the ideal scenario, if 20% permeability of the optional technologies combined with technology improvement, the carbon mitigation potential is further investigated. As shown in Fig. 5, if feedstock altered, the carbon emission in 2030 will be 204.87 $MtCO_2$, with 12.9% additional mitigation potential increased. If the CCS technology incorporated, the mitigation potential is relatively small, with an extra reduction rate of 5.0%. As for the CO_2 hydrogenation technology applied, the situation is a little complex. Due to the great amount of electricity consumption in the water electrolysis process, its generation source will have deep influence on the total carbon emission in the whole process. If electricity is from coal combustion, there is no carbon mitigation potential and the carbon emission will be even increased by 69.1%. However, if renewable electricity is used, such as wind, an extra mitigation potential (10.1%) will be obtained. All in all, the order of mitigation potential is followed as: feedstock alteration > CO_2 hydrogenation application (renewable electricity) > CCS technology incorporation > CO_2 hydrogenation application (coal power).

3.3. *The mitigation cost of different reduction routes*

3.3.1. *The mitigation cost of feedstock alteration*

The product cost of NGTO and CTO routes with similar production scale is firstly estimated as 2015 economic situation (Current price statistics, 2015; China Industry Information, 2017a,b,c). As shown in Fig. 6, when the price of natural gas and coal is 3.3 CNY/m^3 and 400 CNY/t, respectively, the olefin production costs by NGTO and CTO routes are 9738 CNY/t and 5395 CNY/t, respectively. For NGTO route, 78.3% contribution is from the raw material cost, and the rest part is mainly from the utility cost (5.8%) and depreciation cost (8.0%). Therefore, NGTO route will be greatly influenced by the price fluctuation of raw material. For CTO route, the utility cost (30%) and depreciation (23%) is more than that of NGTO due to the more complex production process. However, its contribution from raw material cost (30%) is less.

Furthermore, the mitigation cost of feedstock alteration is calculated. Fig. 7(A) shows the corresponding relationship between mitigation cost and feedstock prices. A zero plane was inserted to divide the mitigation cost. The mitigation cost changes significantly with the fluctuation of feedstock prices. Judging from the slope, it is more affected by the natural gas price than the coal price. The detailed conclusion is listed as follows:

Table 2 – Comparison among different level in term of energy use and emission factor for CTO industry.

			Coal as raw material	Coal as fuel material	Total coal needed
Coal energy requirement (ton coal/ton olefin)	2015 average level		3.2	2.2	5.4*
	2015 advanced level		2.9	2.0**	5.0*
	2020 advanced level		2.6	1.9	4.5
	2030 advanced level		2.4	1.7	4.1
		Emission from upstream	Emission from process	Emission from utility	Total emission
Emission factors (ton CO_2/ton olefin)	2015 average level	.98	5.79	3.15	9.92
	2015 advanced level	.98	5.25	2.86	9.09
	2020 advanced level	.98	4.70	2.72	8.40
	2030 advanced level	.98	4.34	2.43	7.75

* From the data of CTO industry in "12th. Five Plan" period https://wenku.baidu.com/view/b809dd1010a6f524ccbf85e9.html.

** The data is from the scheme of innovation development of modern coal chemical industry released by National Development and Reform Commission in China.

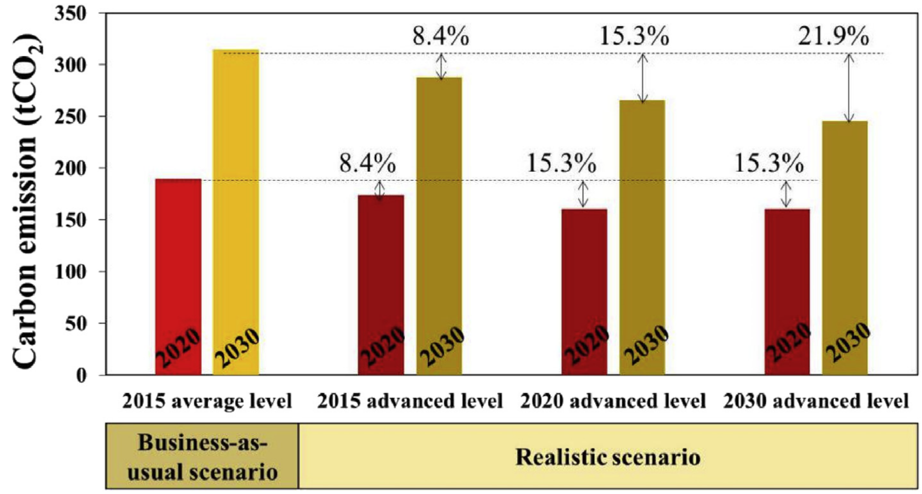

Fig. 4 – The mitigation potential in China's CTO industry under business-as-usual scenario and realistic scenario.

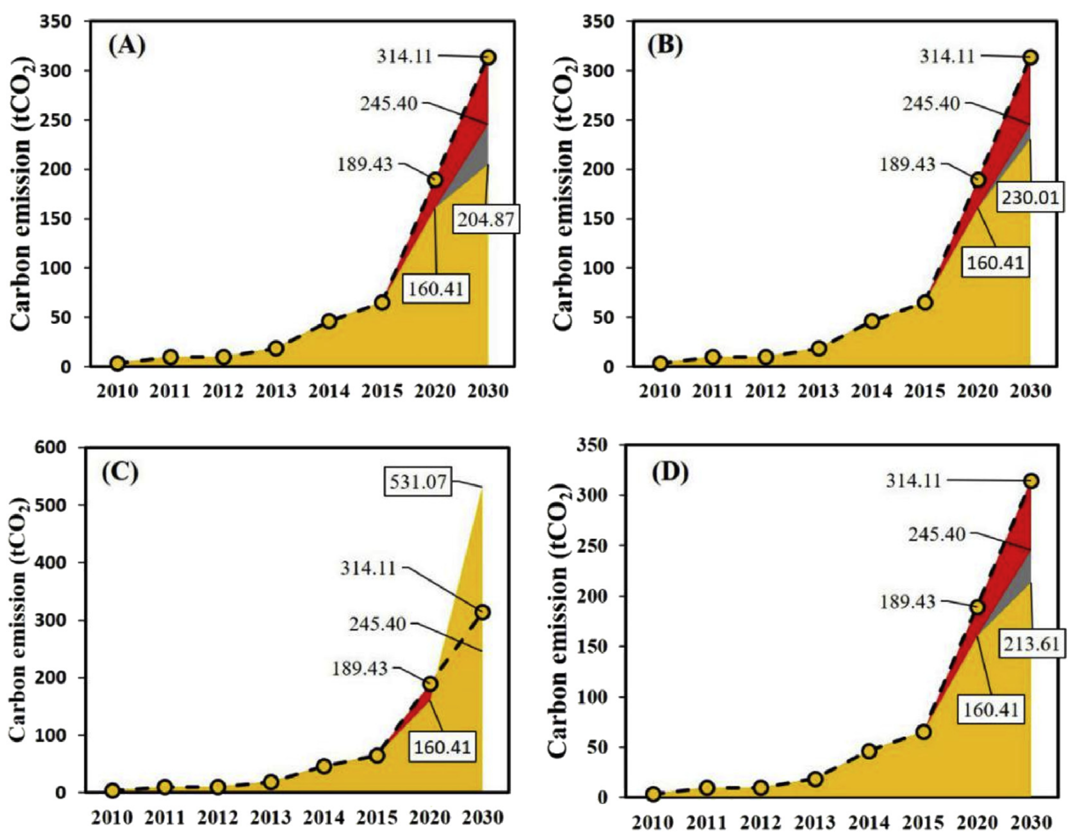

Fig. 5 – The carbon reduction potential of China's CTO industry different ideal scenarios (A) combination of technology improvement and feedstock alteration (B) combination of technology improvement and CCS incorporation (C) combination of technology improvement and CO_2 hydrogenation (electricity from coal) (D) combination of technology improvement and CO_2 hydrogenation (electricity from wind).

(1) when the coal price is ranged between 300 and 700 CNY/t, the mitigation cost will be always above the zero plane if the natural gas is higher than 2.20 CNY/Nm^3. This means that under this situation, the feedstock alteration by natural gas will lead to economic penalty, although the carbon mitigation could be achieved. We can see that when the natural gas price is 3.5 CNY/Nm^3 and the coal price is low to 300 CNY/t, the maximal mitigation cost is 680 CNY/tCO_2.

(2) when the coal price is ranged between 300 and 700 CNY/t and the natural gas is lower than 1.30 CNY/Nm^3, the mitigation cost is always below the zero plane,

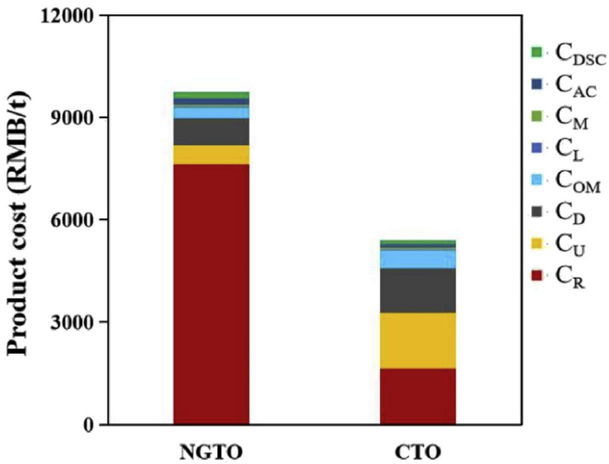

Fig. 6 – The comparison of product cost of CTO and NGTO technologies.

indicating under this situation, not only the carbon emission could be reduced, but also the economic benefits could be obtained.

(3) When the natural gas price is ranged between 1.30 and 2.20 CNY/Nm^3, the relationship between natural gas price and coal price to attain mitigation cost as zero, is shown in Fig. 7(B). Above the critical line, extra mitigation cost is needed. Below the critical line, economic and environmental benefits are simultaneously attained.

3.3.2. *The mitigation cost of CCS technology incorporation*

For the estimation of CCS cost, it is mainly relied on the actual operation cost in Shenhua CCS pilot-scale project. It is reported that this CCS project is designed to inject 300,000 tCO_2 captured from direct coal liquefaction plants into very low permeability (<50 mD) saline aquifers at depths of >1600 m for 3 years. The full cost of operation and construction for the site is about 43 \$/tCO_2 (~270.9 CNY/tCO_2), which includes construction, materials, installation, capture and transportation, surface storage equipment, subsurface equipment, supporting system and miscellaneous cost (Wu, 2014; Zhang et al., 2016). It is noteworthy that Shenhua CCS project has several special characteristics, which will affect its ultimate cost. For example, a CO_2-rich gas mixture with a high concentration of 87% is directly used and the CO_2 is transported by tank trucks with the distance of 17 km. Therefore, to obtain a reasonable CCS total cost, other factors, such as the CO_2 capture and transportation cost should also be considered on the basis of Shenhua CCS project. It is reported that the electricity consumption during the CO_2 captured process is 108 kwh/tCO_2 (Xiang, 2016). For the transportation cost, it is highly dependent on the pipeline length as well as the economies of scale associated with designed CO_2 throughput. The relationship for the calculation of total pipeline capital cost is reported by Dahowski et al. (Dahowski et al., 2012). Therefore, the mitigation cost, selecting Ordos basin as the storage site for CCS technology incorporation in the CTO industry is roughly estimated.

As shown in Fig. 8, the CCS cost is ranged between 360 and 758 CNY/tCO_2 if the transportation distance is ranged between 10 and 500 km and the annual flow rate is ranged between 2.9 and 12.7 $MtCO_2$ per year. As can be seen in Fig. 8, the transportation distance is a more sensitive factor to influence the CCS cost, which is consistent with the literature's result (Nguyen et al., 2017).

3.3.3. *The mitigation cost of CTO with CO_2 hydrogenation technology*

For the estimation of mitigation cost in CTO with CO_2 hydrogenation technology, two situations are also considered. From Fig. 9A, if the electricity is from coal combustion, the obtained values are all negative. In Table 3, we know compared to the

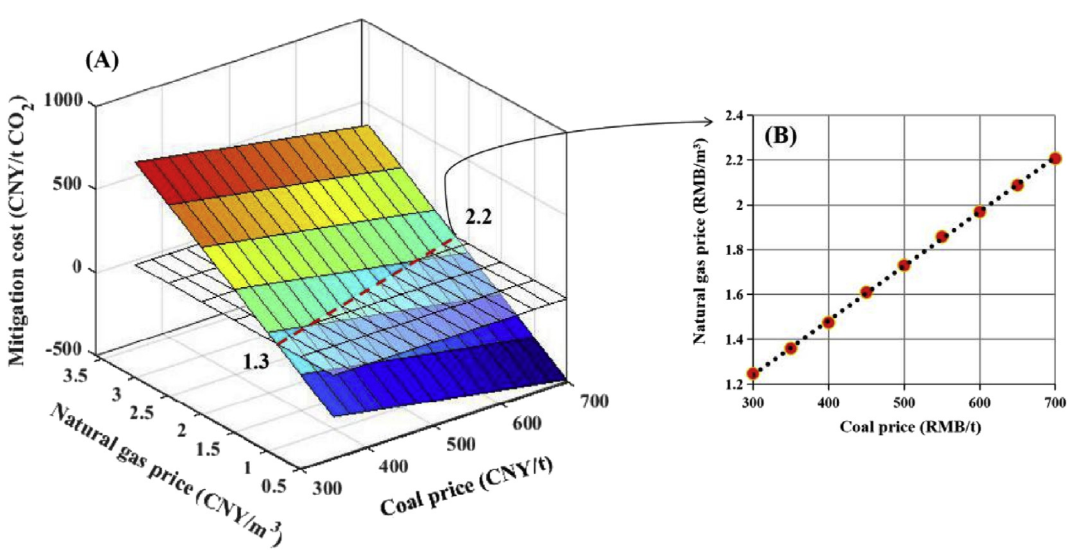

Fig. 7 – (A) viability window of mitigation cost by the replacement of NGTO route under different natural gas price and coal price in CTO industry; (B) the relationship between natural gas price and coal price when mitigation cost is equal to zero.

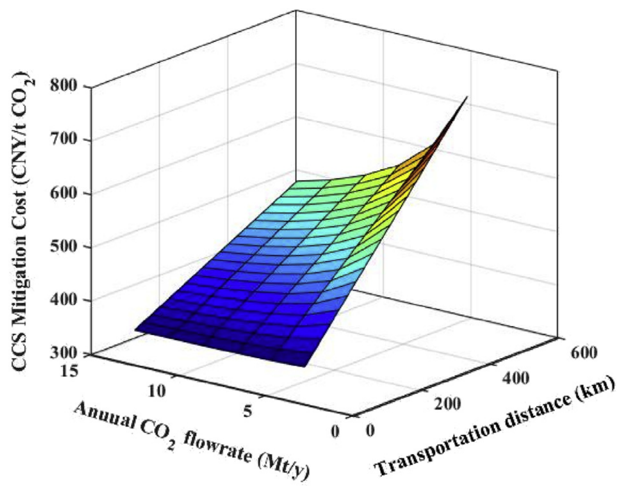

Fig. 8 – Viability window of mitigation cost by the incorporation of CCS technology under different transportation distance and annual flowrate in CTO industry.

situation of original CTO technology without CO_2 hydrogenation technology, the carbon emission is increased due to the horrible electricity consumption for the water electrolysis in CTO with CO_2 hydrogenation technology. Therefore, the denominator is always a negative value in Eq. (2). This results indicate that the incorporation of CO_2 hydrogenation technology in CTO not only leads to the increase of carbon emission, but also brings the economic penalty as a result of the imbalance between the economic efficiency of methanol production and the extra cost. However, if the electricity is from renewable energy, as shown in Fig. 9B, though the carbon reduction could be realized, the mitigation cost is extremely high. For example, if the methanol price is high to 3000 CNY/t and the electricity price is low to 0.2 CNY/kwh, the mitigation cost is till high to 1042 CNY/t CO_2. Therefore, it could be concluded that in CTO, if CO_2 hydrogenation technology with water electrolysis as hydrogen supply, the source of electricity generation is the key to decide whether it is a mitigation way. However, even if the renewable energy is used, the mitigation objective could be realized but the mitigation cost is unacceptable.

3.3.4. *Discussion of mitigation cost*

Based on the above analysis, the mitigation cost of different reduction technologies is compared if the variables are considered on the basis of 2015 values, and the results are shown in Fig. 10. For feedstock alteration, when the natural gas price is 3.3 CNY/Nm^3 and coal price is 400 CNY/t, the mitigation cost is 451 CNY/tCO_2. However, if the coal price is fluctuated to 600 CNY/t, the mitigation cost is decreased to 335 CNY/tCO_2. Furthermore, if the natural gas price is also reduced to 2.7 CNY/Nm^3, the mitigation cost is low to 186 CNY/tCO_2. For CCS cost, if taking Ordos basin as the objective storage site, the mitigation cost of nearest CTO projects in China are calculated. It is seen that the CCS cost is ranged between 404 and 562 CNY/tCO_2. For the CO_2 hydrogenation

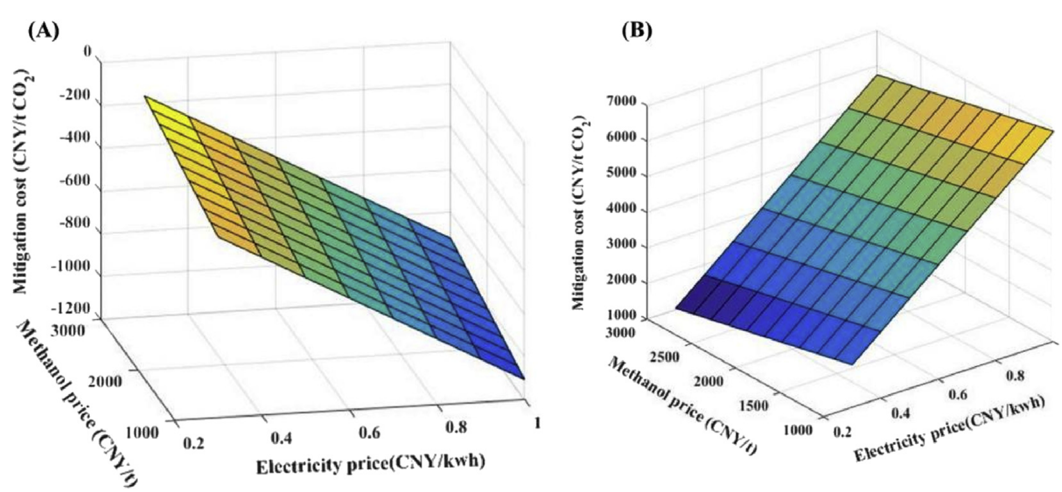

Fig. 9 – Viability window of mitigation cost by the incorporation of CO_2 hydrogenation technology.

Table 3 – Emission factors for different olefin processes.

Processes	Units	Indirect emission from upstream	Direct emission from process	Direct emission from utility	Total emissions
CTO	tCO_2/t olefins	.98	5.79	3.15	9.92
NGMTO	tCO_2/t olefins	.18	0	1.17	1.35
CTO + CCS	tCO_2/t olefins	.98	.24	4.10	5.32
CTO + CO_2 Hydrogenation (coal electricity)	tCO_2/t olefins	.98	0	51.88	52.86
CTO + CO_2 Hydrogenation (wind electricity)	tCO_2/t olefins	.98	0	1.75	2.73

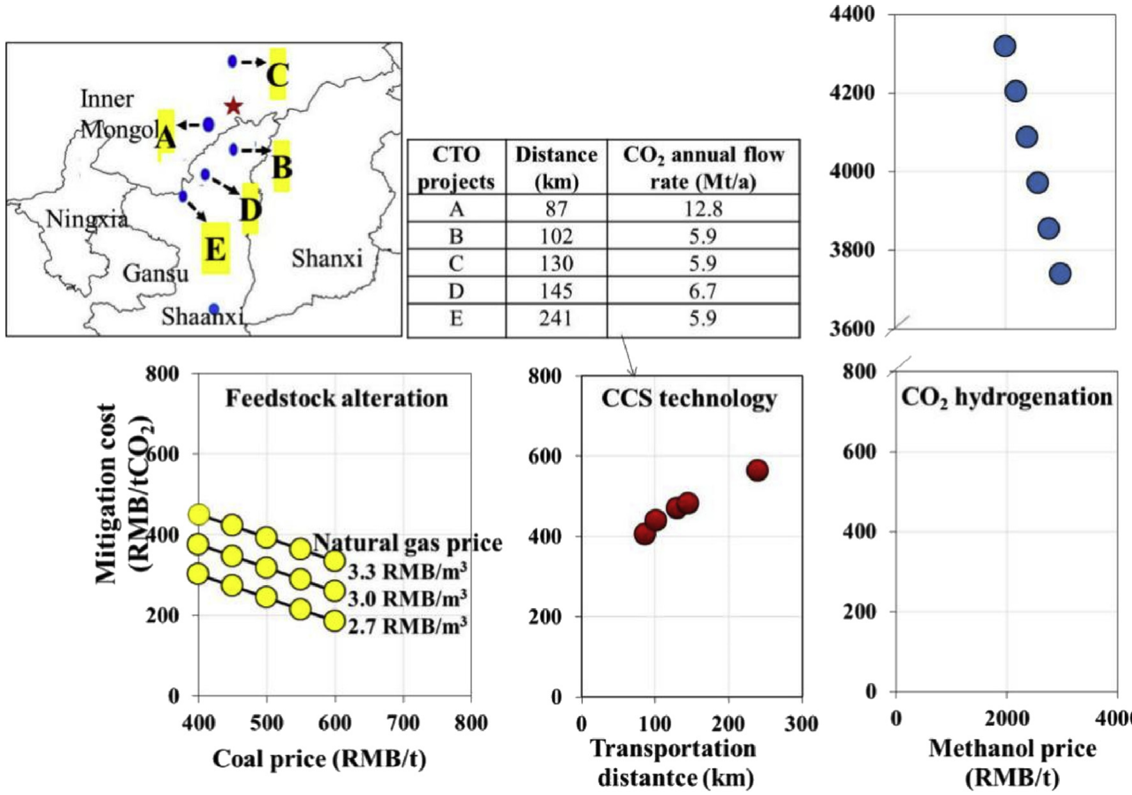

Fig. 10 – The comparison of mitigation cost between different mitigation technologies.

technology, if the electricity price is 0.7 CNY/kwh and the methanol price is ranged between 2000 and 3000 CNY/t, the mitigation cost is terribly high to 3737–4316 CNY/tCO_2.

Therefore, it is clearly shown that feedstock alteration by natural gas is the most promising way. At present, NGTO route is technically matured and was widely industrially applied in the worldwide. In China, due to the shortage of gas resource, the natural gas applied in the chemical industries are limited and the price of natural gas is fixed by government. Therefore, the supply of raw material and economic efficiency is the main bottleneck to hinter its application. The boost of shale gas development in the worldwide may relieve the plight of natural gas shortage in China. China as the largest shale gas reserve nation, with the maturity of its production technology, its shale gas production will be increased rapidly. In addition, owe to the success of shale gas development in United States, the import price of natural gas for China is expected to be low to 1.00 CNY/Nm^3 by 2020 (China Industry Information, 2017a,b,c). Meanwhile, with the collective effects of the policy reform of the oil and gas production and consumption, the cost reduction of natural gas pipeline, and the mechanism change of natural gas price, the natural gas price in China is expected to greatly decline in "13th Five Year" period. It is expected that China's natural gas comprehensive price will decline 23% from 2015 to 2020 (China Industry Information, 2017a,b,c). Therefore, in short term, feedstock alteration is the most feasible mitigation way in CTO industry.

For the CCS technology, it is still under the early development stage, its cost is relatively high, but also acceptable. It is believed that the tolerance of CCS economic penalty will increase for several reasons: (1) with the technology development, the economic penalty will surely reduce; (2) "value-added" storage options, such as the CO_2 enhanced oil recovery could be implemented to increase its economic efficiency; (3) the carbon tax can offset part of the economic cost. For example, in some countries in northern European, the carbon tax is levied and high to more than 50 $/t$CO_2$, even high to 130 $/t$CO_2$ in Sweden (International Energy Data, 2017). However, besides the economic issues, significant efforts are still needed to overcome the technical issues in CCS. For example, more results about the CO_2 leakage degree and the slow rate of CO_2 dissolution in geological formation should be obtained to evaluate the potential safety problems of CCS technology before it is widely applied. In addition, the environmental impact if CCS project operated for a long period, should also be comprehensively evaluated. Therefore, the CCS technology, as an ideal carbon reduction route, has plenty of uncertainties to be defined, and thus there is a still long way for its practical application.

For the CO_2 hydrogenation, if the hydrogen is from the water electrolysis, massive electricity will be consumed, which will be the main factor to decide its environmental and economic efficiency. It seems that if the coal-fired power is applied, the technology will be high-carbon footprint and the resulted carbon emission is even greatly higher than that of the original CTO process. Therefore, the coal-fired power are absolutely prohibited. If the renewable electricity is adapted, the technology is a mitigation way, but the economic penalty seems too high, indicating impossible application at present.

However, there are still some solutions to solve these problems: (1) technology should be improved to reduce the electricity cost; (2) it is necessary to search for more cheap hydrogen sources, such as hydrogen-containing waste gas in some chemical industries; (3) the production chain should be prolonged to obtain high value-added products.

4. Conclusions

In this work, the carbon emission from CTO technology is predicted and the reduction potential by different mitigation pathways is evaluated. It is estimated that the carbon emission of the CTO projects will be attained 189.43 $MtCO_2$ and 314.11 $MtCO_2$ in 2020 and 2030 respectively, almost 3–5 times of that in 2015 (65.23 $MtCO_2$). If the energy efficiency improved, the carbon emission could be maximally reduced by 15.3% and 21.9% in 2020 and 2030. If energy efficiency improvement combined with one of the optional technologies (feedstock alteration/CCS control technology/CO_2 hydrogenation), the mitigation potential will get larger. The order of mitigation potential is followed as feedstock alteration > CO_2 hydrogenation (renewable electricity) > CCS technology incorporation. The mitigation cost analysis indicates that the feedstock alteration by natural gas is the most economical way. The raw material price is the key factor to decide the economic penalty. On the basis of situation in 2015, when the natural gas price is 3.3 CNY/Nm^3 and coal price is 400 CNY/t, the mitigation cost is 451 CNY/tCO_2. For CCS technology, the cost in CTO is also promising to be acceptable under suitable application conditions, which will be 404–562 CNY/tCO_2. However, for the CO_2 hydrogenation technology, the cost is extremely high, which seems impossibly applied at present. Therefore, in short term, feedstock alteration is the most feasible mitigation way for CTO industry and for CCS, it is still worth significant efforts to overcome technical and economic problems.

Declaration of interests

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Carbon Reduction Potential and Cost Evaluation of Different Mitigation Approaches in China’s Coal to Olefin Industry.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jes.2019.11.004.

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