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Article

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Research paper

Cost and potential for CO₂ emissions reduction in China's petroleum refining sector—A bottom up analysis

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ABSTRACT

The petroleum refining sector is energy intensive and has been identified as one of the target industries for CO₂ emissions control by China's emissions trading scheme. A detailed accounting of the cost of emissions reduction is of great significance for the petroleum refining sector to comply with emission reduction target. In this paper, six categories of CO₂ abatement technologies are identified in China's petroleum refining sector, their CO₂ emissions reduction cost as well as the potential are estimated using a bottom-up method. Most of the technologies in the sector are cost-effective, which has contributed approximately 76.4% of sectoral total emissions reduction. New equipment technology provides the greatest contribution to emissions reduction, while new materials technology offers the lowest contribution. The implementation of the emissions trading scheme will increase the potential for emissions reduction only if the CO₂ price can be higher than 200 CNY/t. Given the amount of emissions reduction that technologies can provide will not exceed 40% of the total emissions; firms must find more diversified ways when facing more stringent emissions control.

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1. Introduction

The energy-intensive sectors are primary energy consumption sectors, as well as CO₂ emissions. Reducing the CO₂ emissions in energy-intensive sectors is an inevitable need for industrial sustainable development. In China, as the economic development is to great extent relying on such sectors, the reduction is an urgent requirement for China to cope with climate change. As part of the Paris Agreement, the Chinese government pledges that it would reduce its carbon intensity per unit of gross domestic product (GDP) by 60%–65%, and agrees that its CO₂ emissions would peak in approximately 2030. In order to achieve the targets, domestic energy-intensive industries such as petroleum refining, iron and steel, will be included in the nation-wide Emission Trading Scheme that announced by the Chinese government on December 19, 2017.

The petroleum refining sector is one of most important energy-intensive sectors in China which plays significant role in the economic development. Fig. 1 shows the CO₂ emissions of the petroleum processing, coking and nuclear fuel processing (based on the classification in the China Statistical Yearbook) from 2003 to 2014. For petroleum refining sector, there are several barriers

that prevent the sector to further reduce emissions. First, the refineries within petroleum refining industry are highly heterogeneous, and they are distributed across China. Almost each refinery has unique features in its production process, and finding a unified model to cover all of them is difficult. Second, the sector has already implemented a considerable amount of energy savings and emissions reduction actions during China's 11th and 12th five-year-plans period, and the further potential in CO₂ emissions reduction is also uncertain.

This paper aims to add value to the petroleum refining sector by ascertaining its CO₂ emissions reduction cost curve using a bottom-up method. We examine the cost-effectiveness of different technologies, and assess the CO₂ emissions reduction potential in China's petroleum refining sector by 2020. Furthermore, we provide a viable database that can be adopted to China's petroleum refining sector to calculate the CO₂ emissions reduction costs and improve refineries' ability to cope with CO₂ emissions reduction.

The remaining of the paper is organized as follows: Section 2 provides a review of previous literatures; Section 3 introduces the methodology and data; Section 4 presents the cost and potential of CO₂ emissions reduction analysis; and the conclusion and discussion is shown in Section 5.

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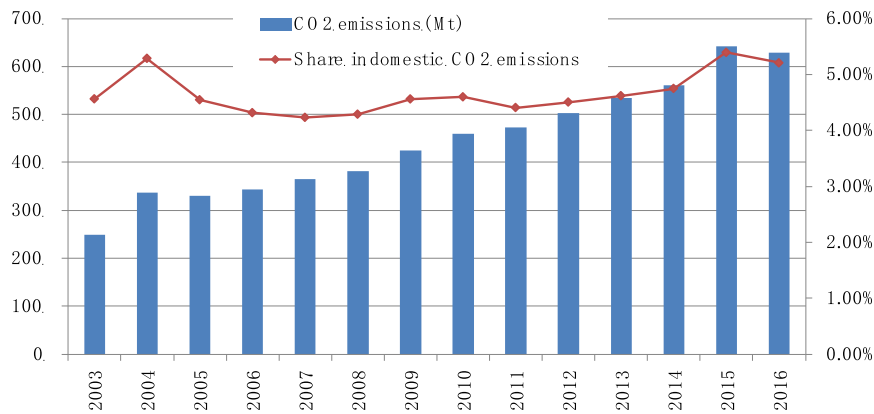


Fig. 1. CO₂ emissions of China's Petroleum processing, coking and nuclear fuel processing industry (2003–2016). Source: Data source: National Bureau of Statistics (2016). Prior to 2003, this sector was referred to as the 'petroleum coking and processing industry' in the Statistical Yearbooks; thus, we only chose the data after 2003 for the purposes of data comparability.

2. Literature review

Given there is always a trade-off between emissions reduction and cost, the proper estimation of costs is considered to be one of the measures to improve the ability of firms to cope with the emission reduction. Two principal methods are applied in the research of emissions reduction costs: one is the top-down method at the macro level (such as the computable general equilibrium (CGE) model), which is mainly used in marginal emissions reduction cost estimation for a country or an area. Rootzen and Johnsson (2015) analyzed different future trajectories of technological developments for Nordic carbon-intensive industries, including petroleum refining, integrated iron and steel production and manufacturing. By simulating the scenarios considering capital stock turnover, technology stock, energy intensities, fuel and production mixes, the results showed the implementation of currently available abatement measures will not be enough to meet the ambitious emissions reduction targets envisaged for the Year 2050. Kajaste and Hurme (2015) analyzed the regional CO₂ emissions in the cement industry by applying a climate impact management matrix on a cradle-to-gate basis, the results showed that the highest near term potential to avoid emissions is by replacing clinker with mineral components.

The other is the bottom-up method at the micro level, which is consisting of a list of available emission abatement technologies and used mainly in marginal emissions reduction cost estimation for a specific sector or firm. The technology-based bottom-up methods have already been adopted to estimate the emission abatement potential in energy-intensive sectors, such as the cement, and iron and steel sectors. Worrell (1995) analyzed advanced technologies and energy efficiency in the iron and steel industry in China. Worrell et al. (2001) analyzed the U.S. cement industry, identifying cost-effective energy efficiency measures and potentials. Hasanbeigi et al. (2010) analyzed the conservation supply curves of Thai cement industry. Worrell et al. (2010) analyzed the energy efficiency improvement and cost saving opportunities for the U.S. iron and steel industry. Fleiter et al. (2012) analyzed energy efficiency and saving potentials in the German pulp and paper industry. Hasanbeigi et al. (2013) estimated the energy efficiency improvement and CO₂ emission reduction potentials in the Chinese iron and steel industry. Li and Zhu (2014) estimated the cost curve of energy saving and CO₂ emissions reduction in China's iron and steel industry which selected 41 energy saving technologies that are widely used or popularized in China's iron and steel industry. Xu et al. (2014)

analyzed CO₂ emissions reduction potential in China's cement industry compared to IEA's cement technology roadmap up to 2050. Wen and Li (2014) analyzed potential energy conservation and CO₂ emission reduction in China's non-ferrous metals industry from a technology perspective. William et al. (2015) identified efficiency improvement and CO₂ emission reduction potentials in the U.S. petroleum refining industry. With the similar bottom up approach, Van de Bergh and Delarue (2015) focused on the relation between a CO₂ emission cost and CO₂ emission reduction in the power sector.

Focusing on the emission reduction in petroleum refining and petrochemical industries, a list of studies has been done from different aspects. Xie et al. (2016) investigated the driving factors of energy-related CO₂ emissions in China's petroleum refining and coking industry by Logarithmic Mean Divisia Index (LMDI) method. They suggested paying more attention to the research and development of energy-saving technology, as well as the clean transformation of energy structure. By gathering the data from different agencies, Adam et al. (2018) adopted the scenario analysis to assess different oil resources and their greenhouse gas intensities, the results showed that the oil production sector has the opportunity to reduce 10–50 gigatonnes of CO₂ eq. by 2050. Based on the description of process flow of a representative U.S. refinery, Yao et al. (2018) established a techno-economic analysis to quantify the national CO₂ emission reduction potential and costs of three types of carbon capture technologies applied to U.S. refineries. Using extended LMDI method, Lin and Wang (2019) analyzed the impacts of different factors on CO₂ emissions in China's petroleum refining and coking industry (PRCI). The findings showed that during 2000–2016, China's PRCI suffered 130.82 million tons CO₂ emissions growth, investment scale expansion was the principal contributor stimulating CO₂ emissions, meanwhile the investment efficiency and energy intensity were two crucial inhibitors.

To best of our knowledge, there is no advanced research on the emission reduction cost of China's refining industry due to the long and complex process in the refining industry. William et al. (2013, 2015) developed a refinery model that consisted of 12 processing units, and they obtained the CO₂ emissions reduction cost curve for the U.S. petroleum refining sector. However, study on the emissions reduction cost in China's petroleum refining sector is still scarce. Given the heterogeneity among refineries, it is difficult to reproduce the model proposed by William et al. (2013) to China. In contrast to William et al. (2013), we do not pay special attention to the process; rather, we divided the CO₂ abatement technologies that are widely used in China's petroleum refining

sector into six categories. And such categorization acknowledged that the processes are completely different among refineries, and one CO₂ abatement technology could be used in more than one process. As a result, we then analyzed the technological options, cost, and potential of CO₂ emissions reduction in China's petroleum refining sector.

3. Methodology and data

3.1. Boundary of the research

The clear identification of CO₂ emissions sources, whether based on final consumption or product life cycle, is a challenge due to the complex production process and the diverse product categories of the petrochemical sector. The petrochemical sector includes a long industrial chain and several sub-industries, which may be divided into petroleum and natural gas exploitation, petroleum refining, chemical raw materials and product manufacturing, etc. Considering that petroleum refining is the most important and the most energy-intensive process in the petrochemical industry, we chose it as the subject of investigation. That is, in the complex process of the petrochemical industry, we consider only the refining of crude oil to various petroleum products, which we refer to as the 'petroleum refining sector' in this paper. The boundary of the devices is shown in Fig. 2.

3.2. Technology selection and data description

We chose the best available technologies (BATs) to investigate the cost of CO₂ emissions reduction in China's petroleum refining sector. BATs are the most effective, advanced and energy-efficient technology and equipment that are currently available within a sector. The sector can obtain significant economic and environmental benefits through the application of BATs, which offer the following three valuable advantages: the first is the integration of technologies, including the design, installation, maintenance and operation of each technology; the second is the availability of technologies, which refers to the actual and economic results that could be obtained in production; and the third is the optimality of technologies, which could lead to the best economic and environmental benefits.

In this paper, the CO₂ abatement technologies of the petroleum refining sector are classified into the following six categories. Given there is no unified classification for such technologies in the petroleum refining industry, our classification is based on the production process and technology features, which are:

(1) Waste-heat recovery and over-bottom pressure recovery technology. Recover the waste heat and over-bottom pressure from flue gas, low temperature hot water, steam and other channels through the addition of waste-heat and over-bottom pressure recovery equipment.

(2) New materials technology. New materials that could increase the radiation intensity of furnaces and boilers, as well as could reduce the thermal conductivity of heat (cooling) preservation.

(3) Process optimization technology. Original processes can be optimized for the purpose of energy recovery and energy conversion.

(4) Intelligent system scheduling optimization technology. Through the installation of intelligent software, the energy utilization of an entire plant can be optimally dispatched, thus increasing the energy efficiency of the plant.

(5) Circulating water system energy-saving technology. This includes the transformation of the water pulp, motor and water cooling tower fan in the circulating water field, matching the

volume and lift of water with the user, recovering and reusing the over-bottom pressure of circulating water.

(6) New equipment technology. New equipment that could improve the efficiency of heat transfer and combustion could also regulate the load of the equipment and of the device.

3.3. Conserved supply curve (CSC) method

Supply curves are commonly used in economics research, and the energy-saving supply curve was developed to rank energy-saving investments based on their cost-effectiveness (Meier et al., 1983). The adoption of CO₂ abatement technologies is a key component of any comprehensive strategy for improving energy efficiency and reducing CO₂ emissions in energy-intensive sectors. Therefore, we analyze the costs associated with technologies which can improve sectoral cost-effectiveness and CO₂ emissions reduction. A conserved supply curve (CSC) method is adopted here to rank the technologies according to their costs of conserved CO₂ emissions.

The detailed calculation of the cost of conserved energy (CCE) is shown in Formula (1), in which we subtracted the annual cost of conserved CO₂ emissions in the numerator based on the work of Worrell et al. (2001). We subsequently chose zero as a baseline to analyze the cost-effectiveness of the technologies. Any technology in which the CCE was found to be below zero was considered to be cost-effective, and vice versa. It should be noted that the annual cost of conserved CO₂ emissions is converted from the saved energy and that the cost of any technology's energy consumption is still included in the annual operating and maintenance (O&M) costs.

$$CCE = \frac{\text{Annualized investment} + \text{Annual O\&M cost} - \text{Annual cost of conserved CO}_2 \text{ emissions}}{\text{Annual CO}_2 \text{ emissions reduction}} \quad (1)$$

The calculation of annualized investment is shown as below.

$$\text{Annualized investment} = \text{Capital Cost} \times \frac{d}{(1 - (1 + d)^{-n})} \quad (2)$$

In Formula (2), d represents the discount rate, and n represents the payback period of the CO₂ abatement technologies. Because of the constraint of capital, firms always prefer a short payback time and a high internal rate of return. Here, we made the assumption that all technologies could recover their investments in the same period. In other words, we set a uniform discount rate for all technologies. This approach not only makes the formula easier to calculate but also reflects the investment preference (e.g., short payback time and high internal rates of return) of petroleum refining firms. We selected a discount rate of 20% in our research, and this figure has been referenced in previous studies (Hasanbeigi et al., 2010; Worrell et al., 2001). We then calculated the CCE of each technology on our list and subsequently ranked them in ascending order starting with the least costly option.

This technology-based CO₂ emissions reduction cost curve represents a snapshot of the annual investment cost of all technologies at a given point. The point at the X axis indicates each technology, and the width indicates the annual CO₂ emissions reduction. The point on the Y axis indicates the cost of the CO₂ emissions reduction. Thus, the CSC method provides a clear and easy way to integrate and summarize complex information regarding these technologies, including their investment costs and CO₂ emissions reduction potential.

3.4. Calculations of energy price and CO₂ emissions factors

Based on the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, the

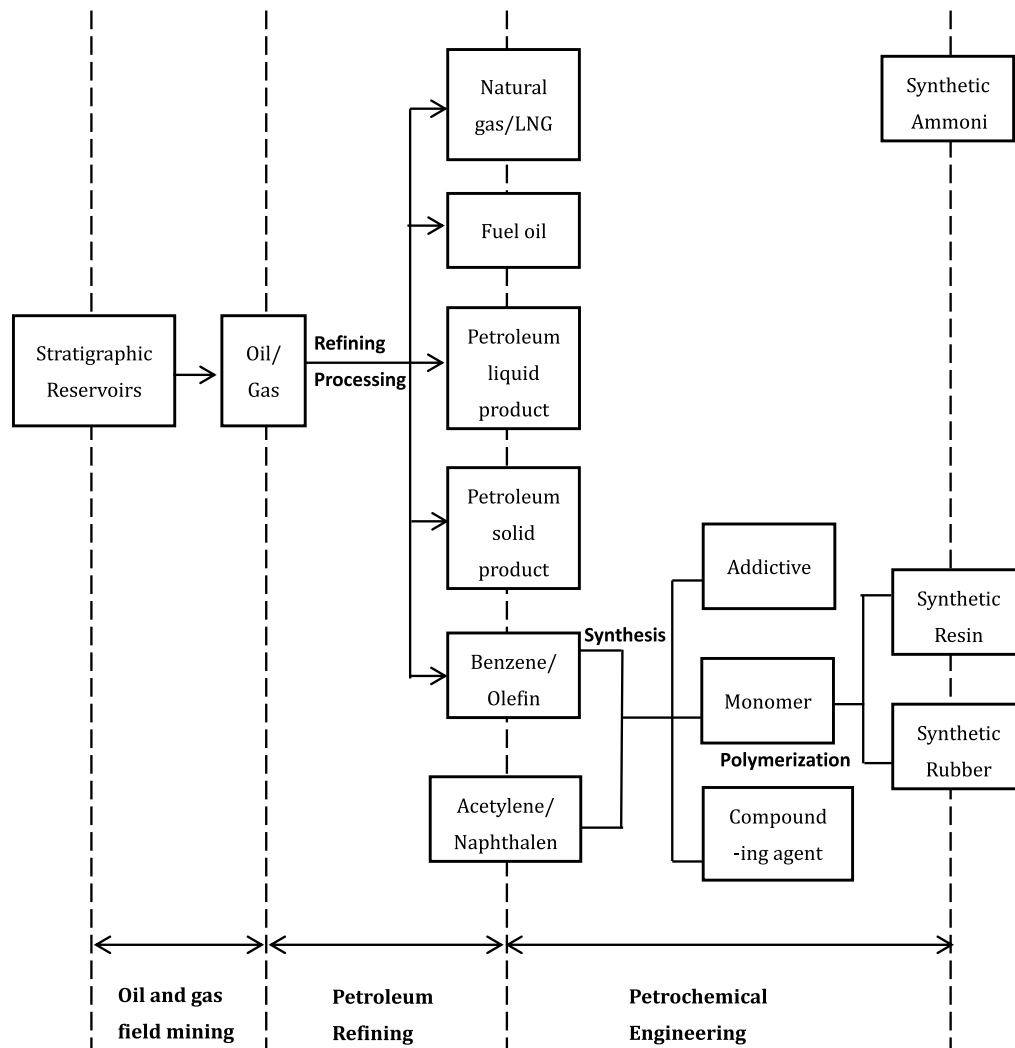


Fig. 2. Production process of petrochemical sector.

emission-factor approach was used to calculate the CO₂ emissions of each technology. The emission-factor approach is often combined with carbon decomposition technology and can be used in the evaluation and decomposition of CO₂ emissions for a period of time in specific areas based on their energy use. Furthermore, it is often used in the analysis of factors that affect CO₂ emissions and could provide guidance for policy formulation. Accordingly, we used the emission coefficient method in this study to measure the CO₂ emissions reduction and its corresponding cost to China's petroleum refining sector. Essentially, the energy consumed by production in the petroleum refining industry was multiplied by the respective emission factors to ascertain the CO₂ emissions of the production process.

The types of energy used most in the petroleum refining sector are coal, petroleum coke, natural gas, electricity and steam. For the convenience of accounting, petroleum coke, natural gas, and steam are converted into standard coal based on their CO₂ emissions factors. Therefore, the energy savings in the petroleum refining sector could be divided into standard coal savings and electricity. This type of conversion method not only adheres to the energy statistic conventions of China's petroleum refining sector but also facilitates a clear and simple comparison of the CO₂ emissions reduction effects of different technologies.

(1) Calculating the price of standard coal. Standard coal has no real price because it is only a thermal unit used to represent

coal; the value is 7000 calories. Therefore, we established a hypothetical price using the following method: Using the average 2016 market price of coal worth 6500 calories as a basis, which was approximately 550 CNY/t (which is equal to 82.5USD/t¹), the price of standard coal could be represented as $7000 \times 550 / 6500 = 592.3$ CNY/t (88.85 USD/t).

(2) Calculating the price of electricity. The price of industrial electricity is different in different areas of China and is also different at peak time, valley time and ordinary time. The price is highest at peak time, i.e., approximately 1.35 CNY/kW h (0.20USD/kW h); lowest at valley time, i.e., approximately 0.55 CNY/kW h (0.08USD/kW h); and is approximately 0.95 CNY/kW h (0.14USD/kW h) at ordinary time. Consequently, we chose to use 0.95 CNY/kW h as the base accounting price of electricity (data comes from the investigation and statistics among refineries in Sinopec Energy Conservation Center).

(3) Calculating the emission factor of electricity. In this study, the calculation of the emission coefficient of electricity is in accordance with the accounting method and report guide for greenhouse gas emissions of China's petrochemical firms (National Development and Reform Commission, 2014). Table 1 shows the CO₂ emissions coefficient of different power grids in China. The emission factor for the North China regional power grid is the

¹ CNY is the abbreviation of the Chinese currency, and 1 CNY ≈ 0.15 USD.

highest, followed by Northeast China and East China. Firms in these areas have higher emissions due to electricity consumption; thus, these firms have higher emissions levels than the firms in the areas of central and North China, even when they have the same levels of electricity consumption. To reflect the efficiency of firms in terms of their electricity use more accurately, we chose the weighted average value of six power grids, which is 0.6858 kg CO₂/kW h, as the combined electricity emission coefficient. It should be pointed out that the selection of unified electricity emission coefficient is to eliminate the influence of incomparable technology contributions in emission reductions among different regions, and such coefficient needs to be adjusted when the CSC method is adopted to specified regions.

3.5. Data statistics and accounting

Table 2 lists the fuel savings (standard coal equivalent), electricity savings, investment costs, O&M costs, CO₂ emissions reductions, and application shares of the 33 selected BATs. The data presented in Table 2 is the actual situation of technology diffusion in the base year, which reflects the share of industry's production with specific technology adopted. The data is collected from the field investigation among China's 26 petroleum refining firms which is done by Sinopec Energy Conservation Center. The investment indicated in Table 2 is the total investment, while the O&M cost is the cost required maintaining the operation of technologies each year. In the case of some technologies that have to purchase electricity and steam during the O&M process, we have deducted this value in the O&M cost accounting and have added this value to the total energy savings instead. Consequently, the energy savings in Table 2 reflects the net value that has reduced the daily energy consumption, while the costs other than the purchasing of electricity and steam are reflected in the O&M costs column. The application share is an estimated value based on the application of a particular technology in all the equipment used in China's petroleum refining sector. Additionally, we have considered the overlap among technologies when estimating the application share; for example, the thermal shield blanket and the SiO₂ Aerogel nanomaterial are both thermal insulation technologies, of which a firm would typically choose only one of them; as a result, neither of the two technologies will achieve a 100% share.

4. The cost and potential of CO₂ emissions reduction analysis

4.1. CO₂ emissions reduction cost curve

Fig. 3 shows the CO₂ emissions reduction cost curve of China's petroleum refining sector when the discount rate is 20%. The technology diffusion rate has been considered when drawing the curves seen below. In 2016, the total CO₂ emissions reduction per unit of production is 0.1345 t CO₂ with these 33 BATs. There are 19 cost-effective technologies (which have negative CO₂ emissions reduction costs), which means these technologies provide benefits beyond emission reduction. The cumulative cost-effective CO₂ emissions reduction per unit of production is 0.1070 t CO₂, which accounted for 79.6% of the total CO₂ emissions reduction per unit of production. In other words, for China's petroleum refining sector, more than two-thirds of the energy savings can be provided by cost-effective technologies. As mentioned in Section 1, given China has promoted the petroleum refining sector to adopt a list of BATs for energy saving and CO₂ emissions reduction during the 11th and 12th five-year-plans, the cost-effective technologies have already occupied dominant market shares in China's petroleum refining sector.

Our work is different from William et al. (2013), in which the petroleum refining process was divided into 12 processing units. Here we focused more on the categories of emission reduction technologies. It is instructive to assess the CO₂ emissions reductions obtained using different types of technologies, as illustrated in Fig. 4. It can be seen that new equipment technology delivers the highest emissions reduction, accounting for more than half (55.21%) of the total emissions reduction. Moreover, new equipment technology benefits from lower investments. The second highest reduction is attributed to the circulating water system energy-saving technology, which accounts for 28.09% of the total reduction. The smallest contribution to the emissions reduction is from new material technology, which accounts for only 0.58% of the total CO₂ emissions reduction. The results reflected in Fig. 4 are in accordance with the actual situation of China's petroleum refining sector, although new materials have gained great attention in recent years, however, limited by high costs and low emissions reductions, large-scale promotion is still unrealistic.

4.2. The impacts of CO₂ price

One of the most important determining factors affecting a firm's decision to purchase CO₂ permits is whether the CO₂ price or the cost of CO₂ emissions reduction is higher. Therefore, we have considered the impacts of different CO₂ prices in our analysis of China's petroleum refining sector. In Fig. 5, the two dotted lines represent the CO₂ price at 100 CNY/t (15 USD/t) and at 200 CNY/t (30 USD/t), respectively. When the CO₂ price is 100 CNY/t, the cumulative cost-effective CO₂ emissions reduction per unit of production is 0.1102 t CO₂, which accounts for 81.9% of the total CO₂ emissions reduction per unit of production; meanwhile, as the CO₂ price increases to 200 CNY/t, the cumulative cost-effective CO₂ emissions reduction per unit of production is 0.1291 t CO₂, which accounts for 95.9% of the total CO₂ emissions reduction per unit of production. It is probable that higher CO₂ prices will promote the diffusion of CO₂ abatement technologies. The increasing number of available cost-effective CO₂ abatement technologies reflects the positive effects of the ETS on the diffusion of BATs.

Fig. 5 also shows that the CO₂ price less than 100 CNY/t did not provide a significant technological boost to China's petroleum refining sector (i.e., the share attributed to cost-effective BATs increased only from 79.6% to 81.9%). The main reason for this difference may be that there are a large number of cost-effective technologies that have been promoted in the petroleum refining sector because the Chinese government attaches great importance to energy conservation and CO₂ emissions reduction. Moreover, the new technologies are in the trial or gradual promotion stages that have relatively higher costs. This difference leads to a large gap in both the cost and the CO₂ emissions reduction between mature and immature technologies, and a lower CO₂ price (i.e., below 100 CNY/t) would be unable to achieve the target of promoting new technologies popularization.

The emissions reduction discussed in this paper is based on technology; other factors, such as catalysts and energy structure adjustments, are not discussed in this article. However, we must realize that the amount of emissions reduction BATs can provide has an upper limit. Here we use CO₂ emissions data from 26 representative refineries in China and investigate the limitations of CO₂ emissions reduction that BATs can provide in the case of carbon pricing. Table 3 shows the CO₂ emissions intensities of 26 Chinese petroleum refining firms (Sinopec Energy Conservation Center, 2016). The CO₂ emissions intensity in Table 3 is the average value obtained from the total CO₂ emissions divided by the total processing quantity of crude oil in 2016. Through

Table 1
The CO₂ emissions coefficient of different power grid in China.

Power grid	Included areas	Emission coefficient (kg CO ₂ /kW h)
North China regional power grid	Beijing, Tianjin, Hebei, Shanxi, Shandong, West Inner Mongolia	0.8843
Northeast China regional power grid	Liaoning, Jilin, Heilongjiang, East Inner Mongolia	0.7769
East China regional power grid	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian	0.7035
Central China regional power grid	Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing	0.5257
Northwest China regional power grid	Shanxi, Gansu, Qinghai, Ningxia, Xinjiang	0.6671
South China regional power grid	Guangdong, Guangxi, Yunnan, Guizhou, Hainan	0.5271

National Development and Reform Commission, 2014.

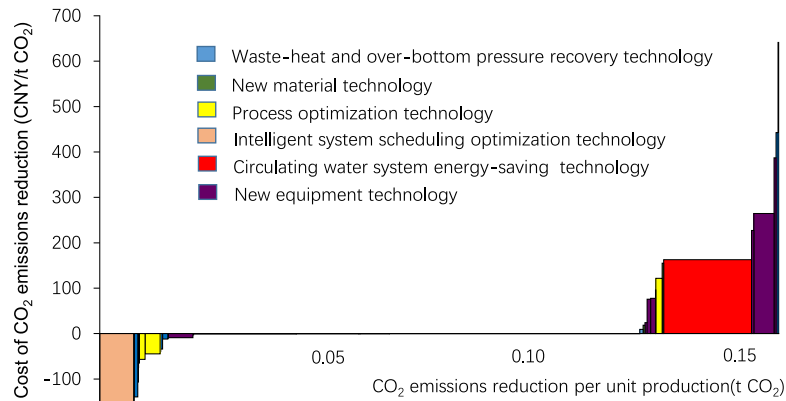


Fig. 3. CO₂ emissions reduction cost curve of China's petroleum refining sector.

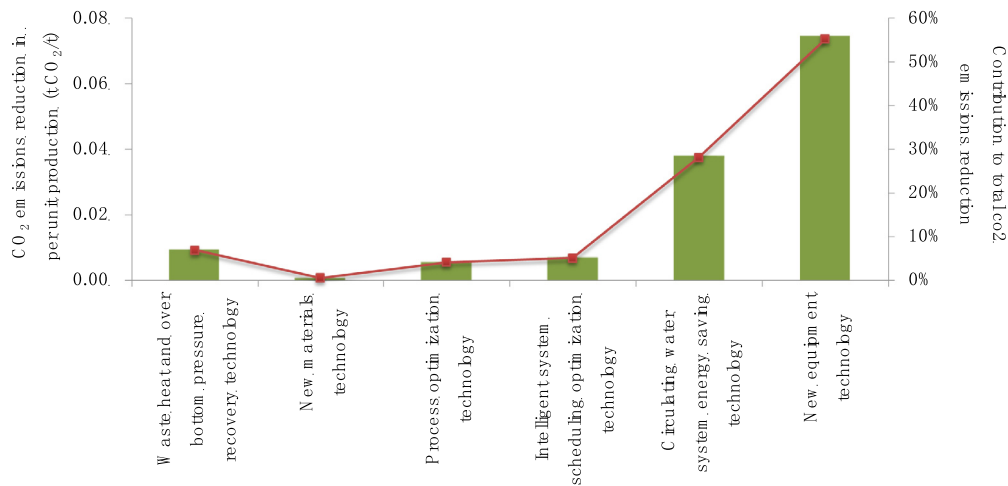


Fig. 4. CO₂ emissions reduction of different types of technologies.

empirical analysis of the CO₂ intensity data of refineries, we intend to analyze how much the current cost-effective technology can reduce emissions, as well as identify the limit of emissions reduction caused by technology adoption.

The average CO₂ intensity of the unit product of China's 26 petroleum refining firms is 0.2220 t in 2016. Without the impacts of CO₂ pricing, the contribution of cost-effective technologies to the cumulative emissions reduction is 0.1070 t CO₂, which accounted for 32.5% (the detailed calculation process is $0.1070/(0.1070 + 0.2220) = 32.5\%$). When the CO₂ price is 100 CNY/t, the contribution of cost-effective technologies to the cumulative emissions reduction is 0.1102 t CO₂, which accounted for 33.2% (calculation processes below are as per the aforementioned method). When the CO₂ price reaches 200 CNY/t, the contribution of cost-effective technologies to the cumulative emissions reduction is 0.1291 t CO₂, which accounted for 36.8%. Finally, when the CO₂ price reaches 500 CNY/t (75 USD/t),

the contribution of cost-effective technologies to the cumulative emissions reduction was 0.1344 t CO₂, which accounted for 37.7% (500 CNY/t is a very high CO₂ price that is hard to achieve; however, it is mainly discussed here to estimate the limit of the impacts of CO₂ price.). A CO₂ price below 100 CNY/t has little effect on improving the proportion of technological emissions reduction in the total emissions. The limit of CO₂ reductions caused by BATs is approximately 37.7%, even when considering the implementation of the ETS.

4.3. CO₂ emissions reduction potential estimation

Based on the data in Fig. 2, we first estimated the 2020 market share of the CO₂ abatement technologies according to the development of the technology, therefore acquiring the potential for CO₂ emissions reductions in the year 2020. The technology diffusion rate is determined by the investigation among the 26

Table 2Key parameters of CO₂ abatement technology in China's petroleum refining sector.

Source: Investigation of Sinopec Energy Conservation Center.

NO.	Category	Technology	Fuel savings (t/a)	Electricity savings (10 ⁴ kW h/a)	CO ₂ emissions reduction (10 ⁴ t/a)	O &M cost (10 ⁴ CNY/a)	Energy saving cost (10 ⁴ CNY/a)	Application share (2016)
1	Waste-heat and over-bottom pressure recovery technology	Energy Conservation Turbine (ECT)	3309	0	0.92	0	195.99	5%
2		Screw expansion drive energy saving technology	0	170	116.59	0	161.5	5%
3		Hydraulic turbine	1470	0	0.41	0	87.07	50%
4		Closed full thermal energy recovery technology for steam and condensate water	13 000	0	3.6	0	769.99	10%
5		Recovery of waste heat from flue gas of desulfurization island and optimization of fan operation	0	198	135.79	0	188.1	1%
6		Waste heat recovery of glass plate heat exchanger	1343	0	0.37	0	79.55	5%
7		Composite phase change heat exchanger	3586	0	0.99	0	212.4	5%
8		Corrugated plate air preheater	21 038	0	5.83	0	1246.08	1%
9	New materials technology	Intensification of heat transfer (Blackbody material)	898	0	0.25	0	53.19	5%
10		High radiation ceramic coating	2700	0	0.75	0	159.92	5%
11		SiO ₂ Aerogel nanomaterials	237	0	0.07	0	14.04	1%
12		Thermal Shield Blanket	976	0	0.27	0	57.81	5%
13	Process optimization technology	Second stage condensing process technology	1653	0	0.46	35.8	97.91	5%
14		Heat high separation process technology	1071	0	0.3	0	63.44	50%
15		Optimization of heat transfer network	7624	0	2.11	0	451.57	30%
16		Waste heat recovery from waste oil in coking process	2000	0	0.55	0	118.46	10%
17	Intelligent system scheduling optimization technology	Optimization and energy saving of steam system operation	36 200	0	10.04	0	2144.13	10%
18		Energy balance and optimal scheduling technology	10 370	0	2.88	0	614.22	10%
19	Circulating water system energy-saving technology	Energy saving optimization technology of industrial cooling circulating water system	4709	0	1.31	0	278.91	40%
20		Mixed flow turbine for industrial cooling tower	0	316.8	217.26	0	300.96	30%
21	New equipment technology	High efficiency single spin heat exchanger	4015	0	1.11	0	237.81	5%
22		High efficiency plate heat exchanger	17 000	0	4.71	0	1006.91	1%
23		Large and high parameter plate and shell heat transfer technology	2900	0	0.8	0	171.77	40%
24		New absorption heat converter	1669	0	0.46	0	98.85	5%
25		High efficiency compound evaporative cooler	0	241	165.28	0	228.95	30%
26		Enhanced heat transfer burner	1948	0	0.54	0	115.38	1%
27		Mechanical vacuum pumping system	2500	0	0.69	0	148.08	30%

(continued on next page)

petroleum refining firms. Fig. 6 indicates the CO₂ emissions reduction potential of China's petroleum refining sector in 2020. According to the predicted technical growth rate, these 33 technologies could deliver 0.1690 t CO₂ emissions reduction per unit of production in China's petroleum refining sector by 2020. Again, 19 of these technologies are cost-effective (because we did not

consider the changes in technology costs, the number of cost-effective technologies is consistent with that in the year 2016), with cumulative CO₂ emissions reduction per unit of production of 0.1442 t CO₂, which accounts for 85.3% of the total CO₂ emissions reduction per unit of production. With the continuous

Table 2 (continued).

NO.	Category	Technology	Fuel savings (t/a)	Electricity savings (10 ⁴ kW h/a)	CO ₂ emissions reduction (10 ⁴ t/a)	O &M cost (10 ⁴ CNY/a)	Energy saving cost (10 ⁴ CNY/a)	Application share (2016)
28		Comprehensive energy saving technology of ball mill with high efficiency ball milling	1260	0	0.35	0	74.63	1%
29		High voltage variable frequency speed regulation technology	1160	0	0.92	0	68.71	15%
30		Flexible traditional energy saving technology for permanent magnet eddy current	0	170	116.59	0	35.15	1%
31		Step-less air conditioning technology	1770	0	0.41	0	104.84	50%
32		Clearance adjustment technology	761	0	0.53	0	45.07	10%
33		Energy saving transformation of steel ball in coal mill	0	0	3.6	0	114	30%

Table 3
CO₂ emissions intensity of China's 26 petroleum refining firms (2016).

NO.	CO ₂ emissions intensity (t CO ₂ /t)	NO.	CO ₂ emissions intensity (t CO ₂ /t)
1	0.1948	14	0.1768
2	0.2839	15	0.1964
3	0.1965	16	0.2275
4	0.3785	17	0.2317
5	0.2179	18	0.2161
6	0.1321	19	0.2646
7	0.2414	20	0.2407
8	0.1615	21	0.1904
9	0.2361	22	0.1799
10	0.1384	23	0.2143
11	0.3214	24	0.1889
12	0.2947	25	0.1992
13	0.2640	26	0.1854

improvement of the diffusion rate of BATs, the cost-effective CO₂ emissions reduction would contribute more in 2020.

A comparison between the potential of the unit product emissions reduction in 2020 and the 2016 equivalent is shown in Fig. 7. The potential for CO₂ emissions reduction per unit of production in China's petroleum refining sector could achieve 0.0345 t CO₂ by 2020. This potential would further increase when the impacts of the nation-wide ETS are considered because CO₂ pricing could promote the adoption of technologies and then increase their diffusion rate.

In addition, to study the development of different technological categories over the next few years, Fig. 8 offers a comparison of the unit product CO₂ emissions reduction in 2016 and the unit product CO₂ emissions reduction potential by 2020 based on the different types of technologies. New equipment technology is still the mainstream approach in China's petroleum refining sector even in 2020. Waste-heat and over-bottom recovery technology and intelligent system scheduling optimization would be promoted quickly in the next few years, while circulating water system energy-saving technology decreases its share of the overall contribution. The second highest is the waste-heat and over-bottom recovery technology, which rise from third place in 2016 to second place in 2020, accounting for approximately 18.25% of the total potential. Meanwhile, intelligent system scheduling optimization technology rise from fourth place in 2016 to third place in 2020, accounting for approximately 16.02% of the total potential. The share of circulating water system energy-saving technology fell sharply, from 28.09% to less than 10%. The smallest contribution still comes from new material technology, which

accounts for only approximately 1.71% of the total emissions reduction potential. Although the proportion has improved (i.e., it accounted for only 0.58% in 2016), new material technology still unable to bear the main responsibility for reducing CO₂ emissions. In Fig. 8, the smaller CO₂ emissions reduction potentials of technologies in 2020 is mainly due to the decreased adoption rate. This shows how much potentials are left for a certain kind of technology. And the results can guide enterprises for technology selection in the future.

5. Conclusion

This paper presents a pioneering study that aims to contribute to the cost and potential of CO₂ emissions reduction in China's petroleum refining sector. We examined the CO₂ emissions reduction cost curve of China's petroleum refining sector through the bottom-up method, which is more consistent with the reality of firms from a micro perspective. A total of 33 technologies were collected for investigation, and a CO₂ emissions reduction cost curve was generated based on the bottom-up CSC method. The results showed that the cumulative emissions reduction of China's petroleum refining sector is 0.1345 t CO₂/t product due to the incorporation of CO₂ abatement technology. More than half of the technologies are cost-effective, and the contribution of cost-effective technologies is 0.1070 t CO₂, which accounts for 79.6% of the total CO₂ emissions reduction. In addition, new equipment technology has delivered the greatest contribution to CO₂ emissions reduction (more than 50%), while the new material technology offers the lowest contribution to CO₂ emissions reduction (less than 1%).

Through the forecasted technology diffusion rate of 2020, the sector will still have a reduction potential of 0.0345 t CO₂/t. Also we use the CO₂ intensity data from 26 refineries in 2016 to study the limit of emissions reduction caused by technical application. It was determined that the contribution of technologies to emissions reduction was approximately 32.5% of the total CO₂ emissions when there was no ETS. And such limit can be reached was approximately 37.7%, if the CO₂ price is no less than 200 CNY/t in the future, as most non-cost-effective technologies will be effectively motivated with CO₂ price level higher than 200 CNY/t.

The curve derived in this paper is of great significance to China's refinery firms. Firstly, it can help firms to know better on their own emissions reduction costs, which is important for them to manage carbon assets. Secondly, it can guide the firms to form their own technology portfolio on emission reduction, which will

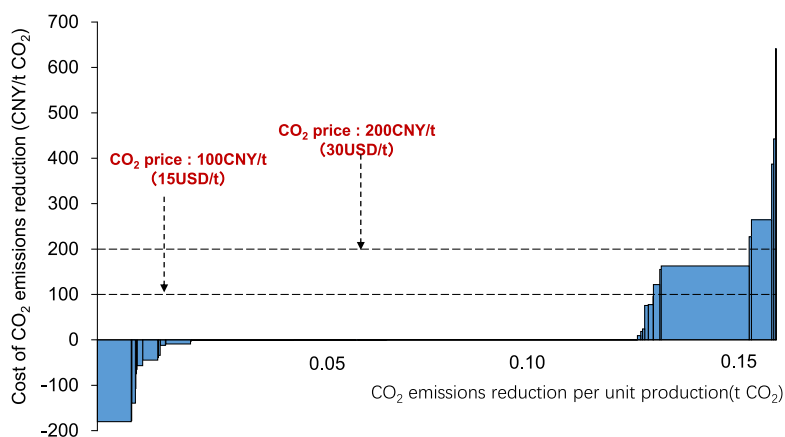


Fig. 5. Impacts to China's petroleum refining sector considering the ETS (2016).

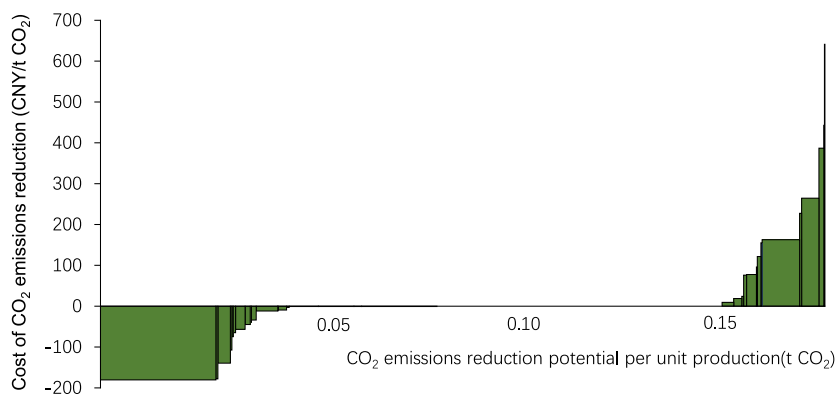


Fig. 6. CO₂ emissions reduction potential in 2020 of China's petroleum industry.

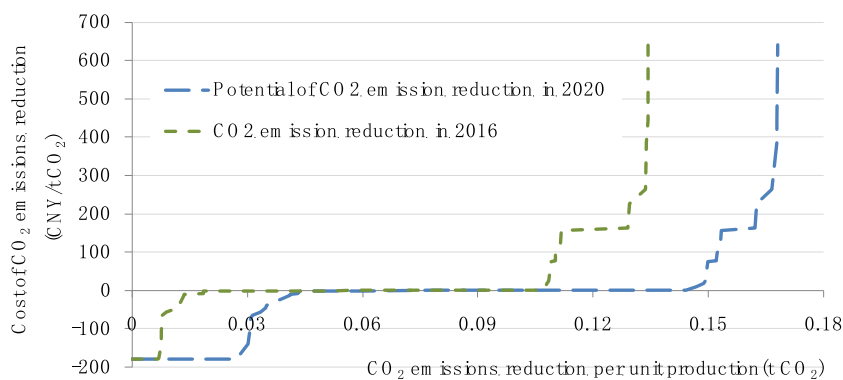


Fig. 7. The comparison between the potential of the unit product emission reduction by 2020 and the 2016 equivalent.

help them to detailed account the CO₂ emissions reduction costs. Thirdly, it can be used as a tool to enhance firms' ability in coping with the ETS.

Given the petroleum refining sector is characterized by complex processes and considerable heterogeneity among refineries, there are still some shortcomings in the research. First, in the use of a bottom-up approach to establish the list of CO₂ abatement technologies, it is possible that some technologies may have been excluded, which would result in an underestimation of the total emissions reduction costs. Second, the reduction cost curve obtained in this study represents only the average level of China's petroleum refining sector; it can be quite different across specific firms. Third, as China's nation-wide ETS has only recently been implemented, the information on CO₂ prices is not yet complete. As a result, the estimation of the potential for further emissions

reductions may not be entirely accurate in this research work. These limitations will be further improved in future work, as new data come to light.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yuan Li: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Beixing Wang:** Investigation, Resources.

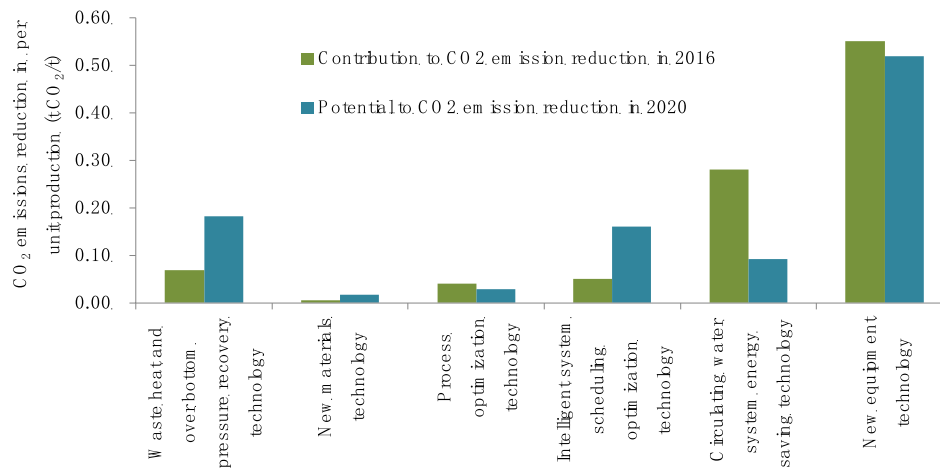


Fig. 8. The comparison of unit product CO₂ emissions reduction in 2016 and potential by 2020 of different types of technologies.

Yanli Xie: Investigation, Resources. **Lei Zhu:** Formal analysis, Writing - review & editing.

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