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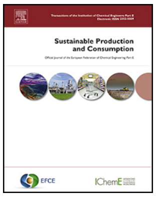

Research article

Does China emission trading scheme reduce marginal abatement cost? A perspective of allowance allocation alternatives

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ABSTRACT

Emission trading schemes (ETSs) are regarded as cost-effective environmental regulatory policies; however, because of the loose carbon allowances, it is up for debate whether China's carbon emission trading scheme (CETS) plays a cost-effective role in carbon emission reduction. This paper investigates how the marginal abatement cost (MAC) is changed by the China CETS from a perspective of alternative allowance allocation methods. The empirical strategy adopts the directional distance function and difference-in-difference (DID) analysis, coupled with the industry-by-province level data from 2008 to 2016. The roles of free-auction combined allowance allocation rules and free allocation in the MAC are explored. Furthermore, the heterogeneous effects of adopted free allocation in CETS, i.e., benchmarking (BENCH), emission-based grandfathering (EGRAND), and intensity-based grandfathering (IGRAND) on MAC of industries are investigated. The empirical findings disclose the following. First, China CETS results in an 8% decline in MAC for the regulated industrial sectors in pilot areas. Second, regulated industrial sectors allocated carbon allowances by free rule decrease their MAC by approximately 1%, while those allocated carbon allowances by free-auction combined rule increase their MAC by 11%. Meanwhile, of the free allocation alternatives, IGRAND causes a 24% increase in the MAC, while EGRAND and BENCH allocation methods lead to insignificant changes in the MAC for the regulated industrial sectors.

1. Introduction

As the most promising market-based instrument for emission reduction, carbon emission trading schemes (CETSs) have been adopted in major economies, including the European Union, Australia, United States, China, Korea, and Canada (Wu and Wang, 2022). China's national CETSs are expected to be the largest ETS in the world, aiming to curb the carbon emissions resulting from its tremendous economic activities. Before the national CETS, during 2013–2014, China initiated CETS pilots including five municipalities and two provinces, i.e., Beijing, Shenzhen, Shanghai, Guangdong province, Tianjin, Hubei province, and Chongqing. Major carbon-intensive sectors such as steel, cement, the chemical industry, electricity generation, aluminum electrolysis were regulated in regional CETS pilots, and nearly 3000 related enterprises exceeding the emission limit were included in the regional carbon market (Munnings et al., 2016). The regional CETS pilots are operated to explore the successful experience in the market efficiency, emission reduction effectiveness, and reasonable and improved policy designs. There, the policy element designs in CETS areas are crucial, especially the rules allocated carbon allowances, which almost determine the effectiveness of these carbon markets. From an allowance allocation point of view, most pilots use free allocation in most regulated industries other than Guangdong, where the auction rule is also combined. In addition, regulated industries in the CETS regions are almost allocated carbon allowances by the three free rules, i.e., BENCH, EGRAND, and IGRANG (Duan et al., 2014).

To combat global climate change, China has improved its nationally determined contributions to emission reduction in 2020, and promises China will achieve carbon neutral around 2060. China's national CETS is a promising and effective way to fulfill these commitments to tackling climate change. In 2020, the national CETS was further pushed forward by publishing the *Measures for the Administration of National CETS* (*Trial Implementation*), and the *Implementation Plan for Cap and Allocation of National CETS in 2019–2020* (*Power Generation Industry*). In July 2021, China's national CEST Officially launched the online trading scheme. At present, only power generation is covered in the national CETS. The

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Nomenclature

Abbreviations

CETS	carbon emission trading scheme
MAC	marginal abatement cost
DID	difference-in-difference
BENCH	benchmarking
EGRAND	emission-based grandfathering
IGRAND	intensity-based grandfathering

Symbols

x	input vector
y	desired output vector
b	undesired output vector
$g=(g_y,-g_b)$	direction vector
$\beta^*=\max\beta$	maximum ability to increase desired output and decrease undesired output
i	provinces
j	industrial sectors
t	years
$CETS_{it}$	dummy variable of China's CETS pilots after the implementation of CETS policy
$Sector_j$	treatment intensity. Average energy consumption per industrial revenue for sub-sector which is covered by CETS, otherwise it equals to 0
X	control variables
$CETS_{i,\,t_0}$	$CETS_{i,\,t_0}=1$ if t_0 is the year before implementing the CETS pilots policy, otherwise $CETS_{i,\,t_0}=0$.
$CETSfree_{it}$	dummy variable representing free allocation
$CETSauction_{it}$	dummy variable representing free combined paid allocation
$CETS\_emissiongrandf_{ijt}$	dummy variable of sub-sector allocated allowances by the emission-based grandfathering method
$CETS\_benchmark_{ijt}$	dummy variable of sub-sector allocated allowances by the benchmarking method
$CETS\_intensitygrandf_{ijt}$	dummy variable of sub-sector allocated allowances by the intensity-based grandfathering method
$Rincome$	GDP per capita
$Rpop$	population
$Rpatent$	granted patents
$IndRD$	industrial research and development investment
$Indfix$	industrial investment in fixed assets
$Indcoal$	industrial energy structure
μ_{ij}	province-industry fixed effect
α_{it}	province-year fixed effect
δ_{jt}	industry-year fixed effect

experiences of the CETS pilots are necessary for improving the design and operation of the national CETS in advance of the inclusion of more industries in the future, especially for the cap setting and allowance allocation.

CETS is a cost-effective instrument for the win-win strategy of emission mitigation and cost-saving, as it causes enterprises with lower marginal abatement costs (MAC) to reduce their emissions to obtain benefits, and enterprises with higher MAC paying fewer emission costs by purchasing carbon allowances through the carbon price mechanism (Akhurst et al., 2003; Cui et al., 2014). Although there is a consensus that China's CETS pilots have made great strides in carbon emission mitigation (Zhang et al., 2020a; Zhang et al., 2019), little is known of the extent to which the abatement costs of the CETS regulated industries are saved. Furthermore, the carbon allowance allocation has a bearing on the allowance stringency and carbon price, which is concerned with the abatement costs involved in curbing carbon emissions. Hence, to provide experiences for the design of the national CETS, it is an urgent and necessary to investigate the heterogeneous effects of the different implemented rules for allocating carbon allowances on abatement costs in the CETS.

Driven by this, the study intends to investigate the casual effects of China's regional CETS on the MAC of carbon emissions, and the different roles of alternative carbon allowance allocation rules in the MAC of the regional CETS pilots. To this end, the panel data of industrial sector in provinces from the period of 2008–2016 are used. The directional distance function is adopted to calculate the MAC of 35 industrial subindustries in 30 provinces, and DID model is used to show the differences in MAC between the regulated and non-regulated industrial sectors in the CETS regions and non-CETS regions, before and after the CETS implementation. Results indicate, first, China CETS has caused a decline in the MAC of the regulated industrial sectors of 8%. Furthermore, the comparison between the free allocation scheme and 'free + auction' (combined) allocation rules of carbon allowances indicate that the former decreases the MAC of regulated industrial sectors by approximately 1%, while the latter increases the MAC by 11%. Meanwhile, the IGRANG causes the industrial sectors to increase their MAC of carbon emissions by approximately 24%, while the EGRAND and BENCH do not lead to any significant changes in the MAC between the regulated industrial sectors and non-regulated sectors.

The following contributions are made to the literature. For one thing, whereas the literature has reached a consensus that China's CETS is effective in carbon mitigation, there still remains a gap regarding the abatement cost savings made in carbon mitigation of China's CETS. This paper intends to fill in this void by estimating the effect of China's CETS on the MAC of covered industrial sectors. For another, of the key elements of CETS pilots, the carbon allowance allocation scheme has a bearing on both the allowance stringency and the carbon price, which determine the abatement cost. This study compares the impacts of different implemented allowance allocation methods, including three 'free allocation' rules, and 'free + auction' (combined) rules on the MAC, to provide more tailor-made policy implications for improving the scientific design of China's national CETS.

The remainder of the paper is organized as follows. Section 2 reviews related literature covering the investigation on CETS. Section 3 explains the methodology used, and introduces the data source, and variable definitions. Section 4 presents the results of the baseline model, robust analysis, and the heterogeneous effects drawn from allowance allocation alternatives. Section 5 concludes the paper and identifies the policy implications.

2. Literature Review

As an effective market-based instrument for curbing carbon emissions, CETSs have been the focus of studies concerning carbon mitigation policies (e.g., Curtis and Lee, 2019; Marin et al., 2018). Previous research into the CETS has highlighted the effects of CETSs from a variety of perspectives of emission mitigation, innovation, economic performance, and competitiveness. For example, by establishing a time-series econometric model, Forbes and Zampelli (2019) find that the EU ETS causes a 6% decline in carbon emissions in Ireland drawn from electricity generation. Nong et al. (2020) carry out simulations in a global energy computable general equilibrium (CGE) framework, to capture the economic impact of Vietnam ETS and observe that the restriction of a considerable number of industries on the Vietnam ETS market leads to a 4.57% decline in real GDP. Löschel et al. (2019) analyze the association between EU ETS and the economic performance in German manufacturing firms based on a DID framework, with the results supporting the positive effects of the regulated firms, especially for the first compliance period. Besides, no identified evidence supports a negative effect. Nava et al. (2018) analyze the association between EU ETS and the competitive effects in the aviation sector with a focus on the abatement efforts by airlines, finding that excessive share of free allowances lowers the incentives to emission mitigation for airlines; while a greater number of airlines competing on the same air route would shrink the profits. On technological innovation, Borghesi et al. (2012) examine whether the first phase of EU ETS has had any effects on the environmental innovation in Italy, and the results suggest that ETS significantly amplifies environmental innovation for consumption level.

China's CETS policy has attracted many studies. There is a lot of previous work pre-estimating its possible contribution to the carbon mitigation by the computable general equilibrium (CGE) model (e.g., Hübler et al., 2014; Nong et al., 2020; Lin and Jia, 2018), and post-estimating the practical effects on carbon mitigation by using policy evaluation methods. Many studies using various methods at the region and industry level have shown that the policy has a pronounced impact on emission mitigation. For example, Qi et al. (2021a), using the DID method, find that the CETS pilots significantly reduce carbon emissions in CETS regions, and that Beijing pilot is the most effective one in carbon mitigation. Leveraging the two-digit industry data at province level between 2005 and 2015, Hu et al. (2020) investigate the influence of China CETS on carbon mitigation and energy conservation, and results of their DID analysis reveal that energy consumption and carbon emissions are mitigated by 23% and 16%, respectively. Similarly, Zhang et al. (2019) use the DID approach to find that China's regional CETS contributes to declining both industrial carbon emissions and carbon intensity. In light of the economic impact, using the DEA-based optimization models, Zhang et al. (2020b) find that both temporal-sectoral trading and sectoral trading schemes may have resulted in the whole industry to gain CNY 612 and 268 trillion from 2006 to 2015. Proposing a new linear programming-based approach, Wu and Gong (2020) conclude that allocation rules on the basis of the sovereignty criterion cause a 3% loss in GDP, while that based on the ability-to-pay criterion could lead to a 24% concussion on GDP. Also, Pan et al. (2022) find that China's CETS has a statistically significant positive impact on the total factor productivity of enterprises, and the positive effect has been maintained for six years since its inception, by using data from A-share listed enterprises from CETS-covered enterprises. However, Wang and Zhang (2022) find that the adverse effect that China's CETS has a negative impact on the market power of high-carbon enterprises mainly through reducing the level of horizontal integration.

In terms of technology innovation, Zhang et al. (2022) employ the spatial Durbin method to show that China's CETS can promote the development of renewable energy by improving green technology innovation. By doing a DID analysis, Zhang et al. (2020b) evaluate the association between China's regional CETS and technology innovation, with results indicating that the CETS policy facilitates technology innovation for the regulated aviation, and power enterprises. As for competitiveness, on the basis of the micro-data of firms in seven energy-intensive industries from 2010 to 2017, Zhang and Liu (2019) use DID method to investigate the impact of China's regional CETS on firms' financial performance, and find evidence supporting its positive impacts on firms in the power industry. In addition, evidence on the significant positive impact on the competitiveness in low carbon field of China's regional CETS is confirmed by Qi et al. (2021b), who use a difference-in-difference-in-difference (DDD) strategy.

Some studies evaluate the abatement cost savings of CETS in China by simulative calculation. Applying an *ex-post* analysis in two scenarios, one with and one without carbon emission permit trading simulation, Xian et al. (2019) provide a simulative calculation of MAC savings from China's CETS in the power industry of 30 provinces. The results indicate that the CETS would reach the MAC savings ranging from CNY 39 to 47/ton. In addition, Wang et al. (2016) assess the MAC of carbon emissions of China's industrial sector between 2006 and 2010. Furthermore, through an ex-post estimation, once the CETS is applied to the industrial sectors across the 30 provinces, they assert the CO_2 abatement cost savings are likely to be realized. Xian et al. (2020) develop a combined parametric and nonparametric approach to calculate the MAC savings of China's regional CETS for the period 2011–2015, finding that they would both exist in almost all regions if the CETS is implemented and if fully operational. Zhou et al. (2013) estimate the MAC curve for China's provinces, developing a nonlinear programming model, showing that China's total emission abatement cost could be reduced by over 40% drawn from the interprovincial CETS. It is worth noting that, in theory, the optimal carbon price of the CETS regulated sectors is equal to the marginal abatement cost in a perfectly competitive market. From this perspective, related existing literature often calculates the MAC curve of different sectors to simulate the optimal carbon price of regulated sectors. For example, by simulating the MAC curve of eight energy-intensive sectors that will be regulated in China's CETS, Tang et al. (2020) analyze the differences in the abatement cost and reduction emissions between sectors, finding the optimal carbon price to achieve carbon intensity goals to be at least CNY 345/ton, while MAC will decline with the increasing number of sectors involved in the CETS.

In summary, previous studies mainly investigate the association between China's CETS and carbon mitigation, economic performance, competiveness, or technological innovation, etc., finding consistent results for its effects on curbing carbon emissions, as well as inconsistent results for its effects on economic performance or technological innovation. Fewer studies discuss the effect of CETS on abatement cost and find the abatement cost that would be achieved due to CETS. There are still several aspects that need to be studied further. First, the limited literature studying the abatement cost savings effect of CETS mainly assesses the potential impacts in assumed scenarios, while there is a scarcity of literature estimating the actual effect of the CETS on abatement cost. Second, the allowances are linked to emission mitigation pressure and carbon price, which directly determines the marginal abatement cost of carbon emissions. Among the implemented allowance allocation methods, which one is the most effective in the operation of CETS pilots, or could be chosen in the application of China's national CETS, needs to be known, but little is revealed in previous research. Considering these limitations, this study uses DID analysis and the industrial data at province level during 2008–2016, to estimate the real effect of CETS pilots on the MAC of carbon emissions. Meanwhile, the heterogeneous roles of the alternative allowance allocation methods (free, free- auction combined, IGRAND, EGRAND, and BENCH) implemented in China's CETS pilots are investigated in MAC.

3. Methodology and data

3.1. Methodology

3.1.1. Quadratic directional distance function

The marginal abatement cost (MAC) of CO_2 emissions denotes the economic cost paid for each additional unit of carbon emission reduction. The directional distance function is often used to estimate the MAC of emissions because it can increase or decrease the ratio of desired output (economic output) and undesired output (carbon emissions) in any proportion and direction (Wei et al., 2013). Provided that *x*, *y*, and *b* represent the input, desired output, and undesired output vectors, respectively, and production technology is $P(x) = \{(y,b) : x\ \ produce\ \ (y,b)\}$, the direction distance function can be expressed as

$$\overrightarrow{D_0} = \left(x, y, b; g_y,\ -g_b\right) = \max\left\{\beta : \left(\mathrm{y}+\beta \mathrm{g_y}, \mathrm{b}-\beta \mathrm{g_b}\right) \in \mathrm{P(x)}\right. \tag{1}$$

where $g = (g_y, -g_b)$ is the direction vector, which means the maximum increase of desired output in the g_y direction and the maximum reduction of undesired output in the $-g_b$ direction. $\beta^* = \max \beta$ is the maximum ability to increase desired output and decrease undesired output.

There are usually two kinds of parameter forms of the directional distance function: the transcendental logarithmic function form and quadratic function form. Some studies have shown that the quadratic function is better than the transcendental logarithmic function form; in most cases, the quadratic function satisfies the transfer property and flexibility of the directional distance function (Vardanyan and Noh, 2006). Therefore, the quadratic directional output distance function is selected as

$$\overrightarrow{D_0} = (x, y, b; 1, -1) = \alpha_0 + \sum_{n=1}^{3} \alpha_n x_n + \beta_1 y + \lambda_1 b + \frac{1}{2}\sum_{n=1}^{3}\sum_{n'=1}^{3} \alpha_n \alpha_{n'} + \frac{1}{2}\beta_2 y^2 + \frac{1}{2}\lambda_2 b^2 + \sum_{n=1}^{3} \delta_n x_n y + \sum_{n=1}^{3} \eta_n x_n b + \mu y b \tag{2}$$

where economic output and carbon emissions are the desired and undesired output, respectively, and the input variables comprise capital, labor, and energy consumption.

The ratio of the partial derivative of the directional distance function with respect to carbon emissions, and the partial derivative of the directional distance function with respect to economic output, represents the price ratio of the two outputs on the production frontier

$$-\frac{q}{p} = -\frac{\partial D/\partial b}{\partial D/\partial y} \tag{3}$$

where p and q denote the price of economic output and carbon emissions, respectively. Thus, at the technically efficient production frontier, the cost required for the economic output from reducing one unit of carbon emissions, i.e., MAC of the carbon emissions, is

$$q = -p\frac{\partial D/\partial b}{\partial D/\partial y} = -\frac{\lambda_1 + \lambda_1 b + \sum_{n=1}^{3} \eta_n x_n + \mu y}{\beta_1 + \beta_2 y + \sum_{n=1}^{3} \delta_n x_n + \mu b} \tag{4}$$

For Eqs. (1)–(4), the stochastic frontier estimation method is used to estimate the unknown parameters of the directional output distance function, because the SFA relative to the linear programming method has the advantage of taking statistical noise into account (Du et al., 2015). The MAC of carbon emissions of industrial sub-industries in each province is then estimated according to Eq. (4).

3.1.2. Difference-in-difference approach

To examine how China CETS pilots impact the MAC of carbon emissions for the regulated industries, the difference-in-difference (DID) analysis is adopted to compare the MAC changes between the CETS-regulated industries in the pilot areas (treatment group) and the non-regulated industries in the non-pilot areas (control group) before and after the policy implementation.

In contrast to the previous literature regarding CETS pilots launched in the same year, the CETS pilots that have an inconsistent time of launching or implementing their carbon pilot policy are considered, and the provinces are set as the area treatment group after they launch the CETS, otherwise they are set as the area control group. The baseline DID model to estimate the MAC impact for the regulated industries is

$$\ln Mac_{ijt} = \omega_1 CETS_{it} \times Sector_j + \omega_2 CETS_{it} + \omega_3 Sector_j + X\zeta + \mu_{ij} + \alpha_{it} + \delta_{jt} + \xi_i + \psi_j + \upsilon_t + \varepsilon_{ijt} \tag{5}$$

where t, i, and j denote years, provinces, and industrial sectors, respectively. $\ln Mac_{ijt}$ is the logarithm of the marginal abatement cost of carbon emissions. $CETS_{it}$ is a dummy variable of CETS pilots implementing the policy: $CETS_{it} = 1$ if the CETS pilot i (Beijing, Shanghai, Guangdong, Tianjin, Hubei, and Chongqing) implements the CETS policy in year t, otherwise $CETS_{it} = 0$. It should be noted that Beijing, Shanghai, Guangdong, and Tianjin launched their CETS in 2013, while Hubei and Chongqing launched theirs in 2014. $Sector_j$ is a variable distinguishing the CETS-regulated or non-regulated sectors. If j belongs to CETS-regulated industrial sectors, $Sector_j$ measures its energy intensity (energy consumption/industrial revenue), otherwise $Sector_j = 0$.[1] Control variables X consist of the provincial variables, i.e., granted patents ($\ln Rpatent$), income ($\ln Rincome$), population ($\ln Rpop$); and industrial variables, i.e., fixed-asset investment ($\ln Indfix$), R&D investment ($\ln IndRD$), energy structure ($Indcoal$).μ_{ij},α_{it}, δ_{jt}denote the province-industry fixed effect, province-year fixed effect, industry-year fixed effect, and υ_t, $\xi_i$and ψ_j indicate year fixed effect, province fixed effect, industry fixed effect. Thus, the provincial and industrial characteristics in both time-varying and time-invariant are controlled (Shi and Xu, 2018). The coefficient ω_1 of $CETS_{it} \times Sector_j$ measures how the China CETS pilots change the MAC of carbon emissions.

3.2. Data sources

The paper analyzes the samples of 35 industrial sectors in 30 provinces during the period of 2008–2016, and the regions of Hong Kong, Tibet, Macao, and Taiwan are excluded. The production inputs include capital, labor and energy, which are represented by total assets, the average number of employees of industrial enterprises above a designated size, and energy consumption, respectively. Desired and undesired outputs are the revenue from the principal business of industrial enterprises above a designated size and amount of carbon emissions, respectively. The data on carbon emissions and energy consumption are from Shan et al. (2017). Total assets, the average number of employed persons, and revenue from the principal business are obtained from *China Provincial Statistical Yearbooks*. The data of the number of provincial granted patents, regional income and population originate from *China Statistical Yearbooks*. In addition, *China Industrial Statistical Yearbooks* is the source for the data on the fixed-asset investment, the share of coal consumption, and R&D investment.

As China's classification of economic activities for industrial sectors was revised in 2011, we keep consistent with the industrial classification during the sample period. Specifically, we merge the statistical data of sectors “Manufacture of Plastics” and “Manufacture of Rubber” into “Manufacture of Rubber and Plastics” before 2012, which are consistent with that after 2012. Besides, we merge the statistical data of sectors “Manufacture of Railway, Shipping, Aerospace and Other Transport Equipment” and “Manufacture of Automobiles” into the “Manufacture of Transport Equipment” after 2012, which are consistent with that before 2012. Shenzhen pilot is not taken into account because Shenzhen city is in Guangdong province. In addition, 18 CETS-regulated industrial sectors are obtained by means of the combination of the two-digit industrial sectors and the regulated industries in each CETS pilot.

3.3. Variable construction

The CETS pilots' policies are analyzed to determine the decline of the industrial MAC of carbon emissions. The dependent variable is the MAC of carbon emissions, which is calculated by the stochastic frontier approach combined with the quadratic directional distance function. The production inputs include total assets ($\ln capital$), the average number of employees of industrial enterprises above a designated size ($\ln labor$), and energy consumption ($\ln energy$). The desired and undesired output are the revenue from the principal business of industrial enterprises above a designated size ($\ln revenue$) and amount of carbon emissions ($\ln CO_2$). All these variables are defined in logarithmic form.

In addition, some provincial and industrial control variables may have an influence on the MAC. Specifically, the difference in economic development, province size, industry scale, technology level, and energy consumption structure has a significant bearing on the reduction of CO_2

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[1] This setting about $Sector_j$ identifies the heterogeneous shocks originated from the CETS policy of different covered industrial sectors.

emissions and associated economic costs (Ji and Zhou, 2020; Ozturk and Acaravci, 2013; Larson and Yezer, 2015; Wu et al., 2019). At the regional level, GDP per capita (ln*Rincome*), is used to represent economic growth; population (ln*Rpop*) is the proxy for province scale. At the industrial level, fixed-assets investment (ln*Indfix*) is the proxy for industry scale. Granted patents (ln*Rpatent*) and R&D investment (ln*IndRD*) are the proxies for technology progress; while energy structure, is proxied by the share of coal consumption (*Indcoal*). Table 1 provides the detailed variable construction and descriptive statistics involved.

It should be noted that, the MAC of 35 industrial sub-industries in the 30 provinces between 2008 and 2016 are obtained by the quadratic directional distance function and the stochastic frontier method. Table A in the appendix show the coefficients of the variables in the directional distance function in Eq. (2). The average MAC of carbon emission for the 35 industrial sectors is approximately CNY 15/ton. At the province level, places such as Jiangxi, Hainan, Qinghai, Chongqing, Ningxia, and Heilongjiang have a greater MAC of industrial carbon emissions, with Jiangxi reaching CNY 70/ton. However, provinces such as Beijing, Guangdong, Shandong, Jiangsu, and Zhejiang have the lowest MAC at less than CNY 10/ton. At the industry level, energy-intensive and high-emission industries, such as Chemical Fiber, Nonmetal Minerals Mining and Dressing, Smelting and Pressing of Ferrous Metals, and Petroleum Processing and Coking have a greater average MAC at over CNY 20/ton. The MAC of Petroleum Processing and Coking can be as high as CNY 100/ton.

Table 2
Effects of China's regional ETS on the MAC of carbon emissions.

	MAC			
	(1)	(2)	(3)	(4)
$CETS_{it} \times Sector_j$	−0.087***	−0.086***	−0.084***	−0.084***
	(0.025)	(0.025)	(0.024)	(0.024)
CETS	0.015	−0.023	−0.017	−0.011
	(0.045)	(0.044)	(0.041)	(0.043)
Sector	0.078***	0.078***	0.075***	0.076***
	(0.026)	(0.025)	(0.024)	(0.024)
lnRincome		−0.072	−0.075	−0.101
		(0.149)	(0.146)	(0.147)
lnRpop		0.284	0.290	0.309
		(0.371)	(0.362)	(0.369)
lnRpatent		−0.015*	−0.016*	−0.010
		(0.009)	(0.009)	(0.018)
Indcoal		0.001	0.001	0.003
		(0.008)	(0.008)	(0.007)
lnIndfix		0.123***	0.120**	0.107**
		(0.046)	(0.045)	(0.045)
lnIndRD		−0.125***	−0.123***	−0.135***
		(0.042)	(0.043)	(0.044)
Observations	6783	6129	6129	6118
R^2	0.202	0.203	0.216	0.221
Province Fixed Effect (FE)	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Province-Industry FE			Y	Y
Province linear trend				Y
Industry linear trend				Y

Note: The clustered standard errors are reported in parentheses.
*** Denotes the significance at the 1% level.
** Denotes the significance at the 5% level.
* Denotes the significance at the 10% level.

4. Empirical results and discussion

4.1. Main results on MAC of CETS policy

Employing the DID approach presented in Section 3.2, first examined is whether China's regional CETS has an impact on the MAC of the industrial sectors regulated in comparison with the non-regulated. The main results of CETS pilots policy on MAC are shown in Table 2, where the columns (1)–(3) control the year, the province, and the industry fixed effects, while the column (4) also controls the province-industry, province-year, and industry-year fixed effects. The standard errors are clustered at the province level in all regressions.

Table 2 indicates that the CETS policy reduces the carbon emissions' MAC of the CETS regulated sectors in CETS pilots, compared with non-CETS regulated sectors. To be specific, results in columns (1)–(4) suggest that, controlling either the year, province, industry fixed effects, or the province-industry, province-year, and industry-year fixed effects, the treatment effects are negative at the 1% significance level. This denotes China's regional CETS effectively reduce the MAC of carbon emissions of regulated sectors. Generally, China's regional CETS policy causes the MAC of carbon emissions of CETS regulated sectors in CETS regions to decrease by about 8%. Hence, the average MAC savings of regulated sectors could range from CNY 0.43/ton to 7.67/ton. Xian et al. (2019) and Xian et al.'s (2020) simulation analysis also find that the MAC savings would be obtained by introducing a fully operating CETS in China. Our finding shows slightly lower number than Xian et al. (2019), who discovered that the MAC savings of the power industry in the 30 provinces ranging from CNY 39 to 47/ton would be realized through China's CETS. The difference may lie in the different research aims and evaluation methods. Xian et al. (2019) evaluate MAC savings in China's power industry from CETS by the simulation analysis, while this paper evaluates the effect of CETS on MAC savings in China's 35 industrial sectors by DID analysis.

There are two main reasons for the results. On the one hand, as a cost-effective way of emission reduction, CETS makes enterprises whose MAC is lower than the carbon price to spare no effort to reduce their carbon emissions for the sake of selling extra carbon allowances in the carbon market to obtain profits. However, enterprises whose

Table 1
Descriptive statistics.

Variables	Meanings	Observations	Means	Std. dev.	Minimum	Maximum
ln*MAC*	Marginal abatement cost	6783	15.622	169.18	1.955	13,299
lnCO_2	Carbon emissions	9158	3.296	2.497	−3.554	10.433
ln*capital*	Total assets	8273	5.453	1.869	−3.219	10.151
ln*labor*	Number of workers	7111	1.107	1.763	−4.605	5.833
ln*energy*	Energy consumption	9028	3.168	2.334	−4.988	9.633
ln*revenue*	Revenue from the principal business	7928	−2.682	1.070	−9.156	5.567
ln*Rincome*	GDP per capita	9450	10.534	0.506	9.196	11.680
ln*Rpop*	Population	9450	8.184	0.740	6.317	9.306
ln*Rpatent*	Granted patents	9450	10.229	1.254	6.066	12.761
Indcoal	Industrial energy structure	9330	0.189	0.283	0.000	3.800
ln*Indfix*	Industrial investment in fixed assets	8700	7.868	1.034	4.975	10.027
ln*IndRD*	Industrial R&D investment	9450	4.310	1.636	−1.555	7.502

Note: MAC are estimated by the quadratic directional distance function.

MAC is higher than the carbon price choose to take moderate measures to reduce carbon emissions while purchasing carbon allowances in the carbon market to achieve their compliance. Consequently, in controlling the industrial total carbon emissions, CETS reduces carbon emissions by cost-effectiveness, and the industrial MAC of carbon emissions is reduced.

On the other hand, in light of the Porter Hypothesis, environmental regulation fosters innovation for companies instead of increasing their cost (Brandi et al., 2020). It is likely that the CETS policy induces more low-carbon technologies for regulated firms, thereby benefits from improved innovations and productivity may compensate the compliance cost. To seek more profits from selling carbon allowances, enterprises with a lower MAC tend to have a greater incentive to innovate or take measures to further reduce their MAC and increase their amount of carbon emission reduction. For enterprises with a higher MAC, the purchase of carbon quota for reducing emissions also increases expenditure. Therefore, to curb the cost of carbon emissions, enterprises introduce energy-saving and emission-reduction technology and carry out R&D into low-carbon technology to reduce their carbon emissions and MAC. Hence, the average MAC of the CETS regulated sectors declined significantly.

4.2. Robustness checks

4.2.1. Placebo test

The empirical results of the DID analysis shows that China's regional CETS reduced the MAC of the carbon emissions of industrial CETS-regulated sectors. To further guarantee this treatment effect does result from China's regional CETS rather than confounding factors that may change MAC, a placebo test is carried out by comparing the significant difference in the treatment effects by assuming that the treatment year is before the actual CETS year, shown as

$$\begin{aligned}\ln Mac_{ijt} &= \omega_0 CETS_{i,t_0} \times Sector_j + \omega_1 CETS_{it} \times Sector_j + \omega_2 CETS_{it} \\ &+ \omega_3 Sector_j + X\zeta + \alpha_{it} + \delta_{jt} + \mu_{ij} + \xi_i + \psi_j + \upsilon_t + \varepsilon_{ijt}\end{aligned} \tag{6}$$

where $CETS_{i,\ t0} = 1$ if t_0 is the year before implementing the CETS pilots policy, otherwise $CETS_{i,\ t0} = 0$. Specifically, for Hubei and Chongqing, $CETS_{i,\ t0} = 1$ when $t_0 = 2013$; while, for Beijing, Shanghai, Guangdong, and Tianjin, $CETS_{i,\ t0} = 1$ when $t_0 = 2012$, otherwise $CETS_{i,\ t0} = 0$. A significant coefficient ω_1 of $CETS_{it} \times Sector_j$ and non-significant coefficient ω_0 of $CETS_{i,\ t0} \times Sector_j$ indicates that, before the actual CETS year, MAC were not significantly changed by the CETS placebo. However, MAC are significantly changed by the actual CETS. Thus, the changes in MAC are a result of China's regional CETS rather than other confounding factors.

The results of the placebo test are shown in columns (1) in Table 3, which indicates that coefficient of the interaction terms in MAC is not significant before the year of CETS implementation, while it is significant after the CETS implementation year. The results indicate that there is no significant difference between the MAC of regulated industrial sectors in the CETS placebo year. However, it significantly declined in the actual CETS years, compared with non-CETS regulated sectors in non-CETS regions. Therefore, the reduction in MAC of carbon emissions is derived from the CETS pilot policy initiated in 2013–2014 rather than other confounding factors.

4.2.2. PSM-DID

To eliminate selection bias and ensure the accuracy of the results of the DID method, the PSM is conducted of the 30*35 provinces and sectors, including the 6 treated pilots and 24 controlled provinces, and the 18 CETS regulated sectors and 17 controlled sectors. Matching variables are the GDP per capita (*lnRincome*), population (*lnRpop*), and granted patents (*lnRpatent*) when conducting the PSM to provinces; and matching variables are R&D investment (*lnIndRD*), fixed-assets investment (*lnIndfix*), and share of coal consumption (*Indcoal*) when conducting the PSM to sectors. Logit model is used to estimate the propensity score and nearest-neighbor matching is conducted for PSM. The PSM results reveal the observations that fail to meet the common support assumption or have extraordinarily high or low probability of being selected as a treated province or sector (Fu et al., 2020). Therefore, they are excluded from further DID analysis. The PSM-DID regression results are shown in Table 3, in which columns (2) and (3) are the results of the DID analysis after the PSM to provinces and sectors, respectively. The PSM-DID results also show that the CETS pilots in China do lead to the reduction in the MAC of carbon emissions for the CETS-regulated sectors, compared with the non-CETS regulated sectors in the non-CETS pilots, which is consistent with the results of the baseline regression.

Table 3
Robustness check.

	MAC		
	Placebo test	PSM to provinces	PSM to sectors
	(1)	(2)	(3)
$CETS_{it} \times Sector_j$	−0.079***	−0.009***	−0.069***
	(0.023)	(0.001)	(0.020)
$CETS_{i,t0} \times Sector_j$	−0.114		
	(0.200)		
lnRincome	−0.407***	0.162*	−0.164
	(0.064)	(0.077)	(0.287)
lnRpop	−0.330	0.535	0.760
	(0.339)	(0.347)	(0.652)
lnRpatent	−0.014	−0.004	−0.015
	(0.008)	(0.007)	(0.052)
Indcoal	0.013*	−0.032	0.260**
	(0.007)	(0.042)	(0.117)
lnIndfix	0.029	−0.079*	−0.269**
	(0.029)	(0.041)	(0.106)
lnIndRD	−0.019	−0.059	−0.050**
	(0.022)	(0.093)	(0.020)
Observations	6129	6043	6129
R^2	0.203	0.178	0.178
Province Fixed Effect (FE)	Y	Y	Y
Industry FE	Y	Y	Y
Year FE	Y	Y	Y
Province-Industry FE	Y	Y	Y
Province linear trend	Y	Y	Y
Industry linear trend	Y	Y	Y

Note: The clustered standard errors are reported in parentheses.

*** Denotes the significance at the 1% level.

** Denotes the significance at the 5% level.

* Denotes the significance at the 10% level.

4.3. Heterogeneous effect of alternative allowance allocation methods

Carbon price is the critical issue in the CETS, as the signal for the carbon reduction strategy choices among abatement cost reduction, allowances purchase or non-compliance of CETS regulated enterprises. The carbon price is closely related to the allocation of quotas (supply), thus the allocation methods. However, because of the allowance allocation, the carbon allowances are generally too loose for the regulated enterprises, the pressure of emission reduction is low, and the cost-effective way for emission reduction could be questionable with alternative allowance allocation. This section therefore analyzes the heterogeneous impacts of allowance allocation alternatives in the CETS pilots on the MAC, to supply more targeted policy implications for the improvement of allowance allocation in China's national CETS.

4.3.1. Heterogeneity in free and free-auction combined allocation

The EU ETS gradually improved its proportion of auctioned carbon allowances in the first and second phases, from 5% to 10%. In line with the EU ETS, China's CETS pilots adopt free allocation as the center, and paid allocation (auction) as associated methods. Of the CETS pilots, the paid allocation was stipulated under the guidance of allowance allocation documents, except for Chongqing; however, only Shanghai, Hubei, Guangdong, and Shenzhen had actual auctions. To analyze how the executed free allocation, and free combined paid allocation affect carbon emissions' MAC of CETS-regulated sectors, we develop the model

$$\ln MAC_{ijt} = \beta_0 CETSfree_{it} \times sector_j + \beta_1 CETSauction_{it} \times sector_j + X\theta + \alpha_{it} + \delta_{jt} + \mu_{ij} + \varepsilon_{ijt} \tag{7}$$

where $CETSfree_{it}$ and $CETSauction_{it}$ are dummy variables representing free allocation and free combined paid allocation, respectively. $CETSfree_{it} = 1$ if the province i adopts free allocation in year t, otherwise $CETSfree_{it} = 0$. $CETSauction_{it} = 1$ if province i adopts the free and auction combined allocation in year t, otherwise $CETSauction_{it} = 0$. It should be noted that, during the sample period, Hubei and Shanghai auctioned a part of their allowances in 2014, and Guangdong auctioned some allowances every year during 2013–2016. In the other cases, pilots allocated all their allowances freely. The coefficients of $CETSfree_{it} \times sector_j$ and $CETSauction_{it} \times sector_j$ enables identification of the heterogeneous effects of the free or auction allowance allocation rules on the MAC of carbon emissions.

The differences in the impacts of free and free-auction combined allocation on MAC according to Eq.(7) are shown in Table 4. Results in columns (1) and (2) regress the corresponding samples adopting the free allocation, free-auction combined allocation, respectively; while results in column (3) regress simultaneously the two kinds of samples adopting free and free-auction combined methods. In the last column of Table 4, the results are very close to the results of the former columns.

The results in Table 4 reveal that

(1) the MAC of carbon emissions in the regulated sectors that are freely allocated carbon allowances declined by around 1%, while the regulated sectors adopting the free-auction combined allocation methods increase their MAC by 11%. From Table 4, the coefficients of $CETSfree_{it} \times sector_j$ and $CETSauction_{it} \times sector_j$ are negative and positive at the 5% significance level, respectively, which indicates that the CETS pilots policy leads to a reduction in the MAC of carbon emissions for the sectors with a free allowance allocation, but an increase in those using the free and auction combined allocation method.

Under the regulation of CETS, the government set the goal of total carbon emissions for each industry and the allocated carbon allowances are reduced year by year — thus achieving the overall goal of carbon emission reduction. Enterprises participating in the CETS are faced with three choices (Song et al., 2018): a) use cleaner energy for energy structure optimization or increase investment in R&D to innovate, so as to curb their own carbon emissions, and even control the actual carbon emissions lower than the allocated carbon allowances. The surplus carbon allowances can be sold in the carbon market to obtain extra profits, which are beneficial for reducing enterprises' MAC. b) the enterprises whose actual carbon emissions exceed the allocated carbon allowances buy the carbon allowances from other enterprises at the carbon price to offset their excess carbon emissions. This expenditure on carbon emissions increases the enterprises' MAC. c) they do nothing to reduce their carbon emissions and accept the non-compliance penalty. Fewer enterprises choose this because the penalty is set by the government and is far higher than the cost of investing in R&D or buying carbon permits.

The above analysis reveals that, under CETS, the main factors that determine the MAC include emission reduction costs such as emission reduction initiatives, R&D investment, and carbon price, followed by the difference between the emission target set by the government and carbon allowances – namely, the pressure of enterprise to reduce their emission. For one thing, the total carbon allowances are generally too loose in China's CETS pilots, the pressure on enterprises to reduce their emissions reduction is low, and the effective or high carbon price is hard to be formed. The effect of this is that the allocation of totally free allowances is equivalent to directly helping enterprises to exempt part of the cost of emission reduction. Because of the compliance pressure, they will provide corresponding mitigation funding and technology to reduce the MAC. Eventually, the CETS-regulated industries with the free allowance allocation will reduce the MAC. However, the free-auction combined allocation makes some enterprises pay an extra carbon allowances cost — thus increasing the corresponding MAC. In addition, the auctions in China's CETS pilots are mostly conducted to assist the regulated enterprises to complete their compliance, so they are usually held during the compliance period when the carbon price is often higher in the pilots. Hence, the cost of the auction allowances and the higher carbon price will lead to an increase in the MAC of enterprises participating in the CETS-regulated industries.

4.3.2. Heterogeneity in free allocation alternatives

Furthermore, free allocation is mainly carried out in the pilots for the sectors, among which a few sectors use the IGRAND, some adopt BENCH, and most employ EGRANG. To identify which allowance allocation rule performs more effectively on the MAC of carbon emissions, models are further developed to investigate the heterogeneous effects of the different free allowance allocation methods on MAC, aiming at providing the experience for China's national CETS policy in terms of allowance allocation, expressed as

$$\ln MAC_{ijt} = \beta_0 CETS\_emissiongrandf_{ijt} + \beta_1 CETS\_benchmark_{ijt} + \beta_2 CETS\_intensitygrandf_{ijt} + X\theta + \alpha_{it} + \delta_{jt} + \mu_{ij} + \varepsilon_{ijt} \tag{8}$$

where the dummy variables $CETS\_emissiongrandf_{ijt}$, $CETS\_benchmark_{ijt}$, and $CETS\_intensitygrandf_{ijt}$ represent the different free allowance allocation methods. If j industrial sector of i province adopts the EGRANG in t year, $CETS\_emissiongrandf_{ijt} = 1$, otherwise $CETS\_emissiongrandf_{ijt} = 0$. Similarly, if it adopts the BENCH, $CETS\_benchmark_{ijt} = 1$, otherwise $CETS\_benchmark_{ijt} = 0$. However, if it employs the IGRAND, $CETS\_intensitygrandf_{ijt} = 1$, otherwise $CETS\_intensitygrandf_{ijt} = 0$. The regression coefficients of $CETS\_emissiongrandf_{ijt}$, $CETS\_benchmark_{ijt}$, and $CETS\_intensitygrandf_{ijt}$ could recognize the different impacts of the three free allowance allocation methods on the MAC of carbon emissions of regulated industrial sectors.

The differences in the impacts of alternative free allowance allocation methods on MAC according to Eq.(8) are shown in Table 5. Columns (1)–(3) in Table 5 show the results from regressing the

Table 4
Heterogeneous effects of allowance allocation methods on the MAC of carbon emissions.

	MAC		
	(1)	(2)	(3)
$CETSfree_{it} \times Sector_j$	−0.010***		−0.010***
	(0.001)		(0.001)
$CETSauction_{it} \times Sector_j$		0.112**	0.108**
		(0.046)	(0.045)
Observations	6129	6118	6118
R^2	0.178	0.186	0.188
Province FE	Y	Y	Y
Industry FE	Y	Y	Y
Year FE	Y	Y	Y
Province-Industry FE	Y	Y	Y
Province linear tend	Y	Y	Y
Industry linear trend	Y	Y	Y

Note: The clustered standard errors are reported in parentheses. The coefficients of the control variables are not reported.

*** Denotes the significance at the 1% level.

** Denotes the significance at the 5% level.

Table 5
Heterogeneous effects of free allowance allocation methods on the MAC of carbon emissions.

	MAC			
	(1)	(2)	(3)	(4)
$CETSgrandf_{ijt}$	−0.032			−0.030
	(0.042)			(0.042)
$CETSbenchmark_{ijt}$		0.026		0.021
		(0.020)		(0.022)
$CETSintensity_{ijt}$			0.244^{***}	0.238^{***}
			(0.045)	(0.045)
Observations	6118	6118	6118	6118
R^2	0.187	0.186	0.187	0.187
Province FE	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Province-Industry FE	Y	Y	Y	Y
Province linear tend	Y	Y	Y	Y
Industry linear trend	Y	Y	Y	Y

Note: The clustered standard errors are reported in parentheses. The coefficients of the control variables are not reported.
*** Denotes the significance at the 1% level.

corresponding samples adopting IGRAND, EGRAND, or BENCH, respectively. Column (4) exhibits the results from regressing simultaneously the three kinds of samples employing the IGRAND, EGRAND, or BENCH. In the last column of Table 5, results are very close to the results of the former columns.

The results in Table 5 reveal that

(2) the CETS causes the regulated sectors with IGRAND to increase their MAC of carbon emissions by around 24%, while it has an insignificant impact on the MAC of the regulated sectors adopting the EGRAND and BENCH method, respectively. As Table 5 shows, the coefficients of $CETS\_emissiongrandf_{ijt}$ and $CETS_benchmark_{ijt}$are not significant, while the coefficient of $CETS\_intensitygrandf_{ijt}$ is positive at the 1% significance level, which indicates that the CETS pilots policy leads to an increase in the MAC of carbon emissions for the sectors using the IGRAND, while the CETS has no significant impact on the MAC of sectors with other allowance allocation methods.

The sectors using allowance allocation of EGRAND are expected to have no obvious impact on the MAC, as this method allocates more free carbon allowances to the enterprises that emit more carbon, and undertake less task for emission mitigation (Qi and Cheng, 2018). Under these circumstances, it is difficult to form an effective allowances demand and high carbon price in the carbon market, so enterprises take moderate measures at a lower cost, even without efforts, to reduce emissions to achieve emission reduction compliance.

The different free allocated allowances qualify the level of tightness of carbon allowances for the CETS regulated sectors (Jin et al., 2020). The carbon-intensive enterprises that belong to the regulated sectors using the IGRAND will be gradually allocated fewer free carbon allowances because the decline of historical carbon intensity are tightening, which gives more pressure on carbon mitigation for the regulated sectors (Peng et al., 2021). If an enterprise's actual emissions exceed its constraints, it is necessary to purchase some emission allowances from the carbon market, increasing its abatement costs (Zhang et al., 2020b). In addition, the shortage of carbon allowances can further induce an effective demand for carbon allowances and higher carbon prices. The dual effect of the increased shortage in allowances and higher carbon prices is to lead to the increased MAC of sectors using the allowances allocation of the IGRAND. The results show that the sectors using the IGRAND increased their MAC by about 24%.

With the BENCH, the baseline emission of the sector is limited by the way of either the average or advanced criterion of the whole enterprise in the industry. Following this rule, advanced or low emission enterprises that make efforts to contribute to emission reduction, will be allocated more carbon allowances than their actual emissions. However, backward or carbon-intensive enterprises will be allocated fewer carbon allowances than their actual emissions demand. In this way, the emission mitigation pressure of advanced enterprises is lower, while that of backward enterprises is higher. The scarcity of carbon allowances will induce a higher carbon price. With the carbon price rising, the advanced enterprises that earlier adopted a higher intensity of emission reduction measures will be more competitive than enterprises making less or no effort to reduce their emissions, and obtain less cost abatement because of the benefits from surplus carbon allowances. Inversely, enterprises with a weak ability to reduce emissions must pay more to purchase carbon allowances — thus increasing their overall abatement cost of compliance. Therefore, the sector's average MAC will increase or decline depending on the extent to which advanced or lagging enterprises try to reduce their emissions. The results here show there is no significant increase in the average MAC for sectors that use BENCH.

5. Conclusions and policy implications

Leveraging the industrial sectors data across the provinces, this study makes a quantitative assessment of the MAC impacts of China's regional CETS. The MAC of industrial sectors in provinces is estimated by the directional distance function combined with stochastic frontier analysis. The empirical strategy uses the DID model by comparing the marginal abatement costs between the CETS regions and non-CETS regions, regulated and non-regulated sectors, before and after CETS policy. In addition, free-auction combined allowance allocation rules, and free allocation in terms of the IGRAND, EGRAND, and BENCH of the CETS in the MAC are further explored.

Some novel empirical findings are obtained. In particular:

(1) the average MAC of carbon emission for 35 industrial sectors of 30 provinces in China from 2008 to 2016 is approximately CNY 15/ton.
(2) China's regional CETS has led to an 8% decrease in the MAC of carbon emissions for the regulated industrial sectors in the CETS pilots.
(3) the MAC of carbon emissions of the regulated sectors that are freely allocated carbon allowances declined by around 1%, while the regulated sectors adopting the free-auction combined allocation method increased their MAC by 11%.
(4) the CETS causes the regulated sectors with the allowance allocation of the IGRAND to increase their MAC of carbon emissions by around 24%, while it has an insignificant impact on the MAC of the regulated sectors adopting EGRAND and BENCH, respectively.

Some policy implications can be obtained by these empirical findings.

Firstly, as China's regional CETS policy has an effective impact on the reduction in marginal abatement cost of carbon emissions for the regulated sectors. Therefore, as a cost-effective tool for emission reduction, the national CETS can hold greater expectations of meeting China's carbon emission reduction goals. The government could resort to the carbon market as an effective policy tool to mitigate CO_2 emissions to achieve carbon neutrality. More sectors, enterprises and greenhouse gas emission targets should be covered in China's national CETS.

Secondly, three specific situations including 1) the setting for the total carbon permits is loose 2) low carbon price and 3) the primary goal of auction is for compliance remain in China. This has led to the results that China's carbon market reduces the MAC for the sectors that are freely allocated allowances, but instead increases MAC for the sectors by using the combined rules of 'free and auction' approach. In this regard, CETS has no constraining effect on the MAC for those sectors that are allocated allowances by BENCH and EGRAND. This suggests that the government should gradually tighten the total carbon permits, in order to activate the demand for the carbon allowances, and induce cost-effective carbon prices in the carbon market.

Thirdly, the government should gradually implement the auction mechanism at the national level when further expanding the CETS coverage, to satisfy the scarcity rule of carbon permits instead of solely 'compliance'. As 'auction' scheme is one of the most transparent approaches which is market based, it could encourage the regulated enterprises to contribute more emission reduction efforts.

As for the future work, on the one hand, research is needed to establish what roles the total carbon permits and actual carbon prices play and how they affect MAC of the sectors adopting the alternative allowance allocation methods. Likewise, more research needs to be conducted beyond regional or industrial levels of the effect of regulated enterprises with alternative allowance allocations.

Declaration of competing interest

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

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Appendix A

Table A
Estimation of the parameters of the directional distance function.

Coefficients	Variables	Estimation
α_1	ln*capital*	0.047 (0.073)
α_2	ln*labor*	−0.093** (0.038)
α_3	ln*energy*	−0.983*** (0.032)
β_1	ln*revenue*	−0.028 (0.067)
$\lambda_1 = 1 + \beta_1$	$\ln CO_2$	1
α_{11}	$(\ln capital)^2$	0.037*** (0.013)
α_{22}	$(\ln labor)^2$	−0.006 (0.005)
α_{33}	$(\ln energy)^2$	−0.039*** (0.002)
$\alpha_{12} = \alpha_{21}$	$\ln capital \cdot \ln labor$	−0.002 (0.015)
$\alpha_{13} = \alpha_{31}$	$\ln capital \cdot \ln energy$	−0.006 (0.008)
$\alpha_{23} = \alpha_{32}$	$\ln labor \cdot \ln energy$	0.001 (0.007)
$\beta_2 = \lambda_2 = \mu$	$(\ln revenue)^2$,$(\ln CO_2)^2$,$\ln revenue \cdot \ln CO_2$	0.014* (0.008)
$\delta_1 = \eta_1$	$\ln capital \cdot \ln revenue$,$\ln capital \cdot \ln CO_2$	−0.045*** (0.016)
$\delta_2 = \eta_2$	$\ln labor \cdot \ln revenue$,$\ln labor \cdot \ln CO_2$	0.014 (0.132)
$\delta_3 = \eta_3$	$\ln energy \cdot \ln revenue$,$\ln energy \cdot \ln CO_2$	0.029*** (0.008)

Note: ***, ** and * denote the significance at the 1%, 5% and 10% level, respectively. The clustered standard errors are reported in parentheses.

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