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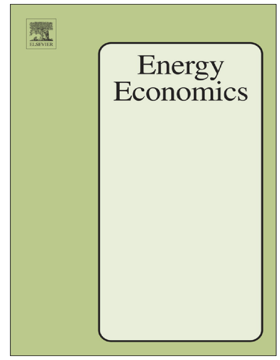

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Carbon Mitigation Effect of Emission Trading Product: Perspective from Intra-Industry Carbon Leakage

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Carbon Mitigation Effect of Emission Trading Product: Perspective from Intra-Industry Carbon Leakage

Abstract: Carbon mitigation within key industries has become a paramount concern in China, yet research focusing on industry-level emissions remains limited despite comprehensive validation of the efficacy of emission trading schemes (ETS) at both enterprise and regional levels. This paper addresses this gap by examining the intra-industry carbon leakage. Firstly, applying multi-period DID method to the industry-level data from 2000 to 2018 in Guangdong province, we empirically find a counterintuitive increase in carbon emissions in the compliance industries despite mitigation efforts by compliance enterprises in the same industries. Secondly, we build a Stackelberg quantity leadership model incorporating ETS and theoretically find that, the intra-industry carbon leakage results in this increased industry-level emissions, notably through the cost crowding-in mechanism. Further theoretical analysis underscores the pivotal role of enhancing ETS coverage ratios for enterprises within compliance industries and bolstering the carbon price mechanism's capacity to accurately reflect enterprises' demand for carbon allowances. Such enhancements are anticipated to effectively mitigate intra-industry carbon leakage and facilitate reductions in industry-level carbon emissions.

Keywords: Carbon mitigation effect; Emission trading scheme; Intra-industry carbon leakage; Cost crowding-in mechanism

JEL: D78, L60, H23

1. Introduction

In the last two decades, China's environmental policies focused on regulating the emissions of high-emitting enterprises in key industries. Nowadays, however, it has been urgent to promote carbon mitigation in key industries as a whole. From an international perspective, the latest global environmental policies have been focusing more on the cross-border carbon leakage, and a large number of policies have directly or indirectly induced higher requirements for China's Greenhouse Gas (GHG) emissions mitigation. For example, the European Union's Carbon Border Adjustment Mechanism (CBAM) will be fully levied in 2026, and the U.S. carbon tariff is also in the process of formulation and introduction, which will have a significant impact on the exports and trades of all Chinese enterprises in the high-emitting industries. From a domestic perspective, the overall reduction of carbon emissions at the industry level has been listed as the next main target in China. In 2021, the Chinese government clearly pointed out that, the carbon emission intensity of key industries such as iron and steel, need to be significantly reduced by 2025.

The emission trading scheme (ETS), which utilizes the market mechanism to control and reduce GHG emissions, has been an important policy tool for the world to achieve net-zero goals. Theoretically, there are two mechanisms for the ETS to reduce the carbon emissions. Firstly, the ETS requires some key enterprises (compliance enterprises) in high-emitting industries (compliance industries) to pay additional emission costs, which internalizes the external costs of the enterprise emissions and forces these enterprises to reduce carbon emission. Secondly, the market-based scheme releases price signals and provides economic incentives to direct funds to enterprises with high potential in carbon mitigation, which provides investment and financing channels for these enterprises to realize low-carbon transformation. Through these two theoretical mechanisms, the ETS promotes key enterprises to reduce carbon emissions and enhance green productivity. At the industrial level, the ETS is further expected to reduce the overall carbon emissions, to facilitate with the transformation of industrial structure, and to realize the low-carbonization of energy consumption.

China's ETS has developed over ten years, and has shown obvious carbon mitigation effects on the key enterprises and the regulated regions. In year 2013, China launched regional pilot ETS markets in eight regions, including Guangdong, Shenzhen, Beijing, Shanghai, etc. In 2021, the national ETS market officially started operation, including 2,162 key enterprises in the power sector in China. Previous studies have confirmed that regional pilot ETS has a significant carbon mitigation effect in the regulated regions compared to the non-regulated regions in China (Zhang et al., 2020b). A similar effect has been found at the enterprise level. Compared to the enterprises not regulated in the pilot and non-pilot regions, the compliance enterprises increase their incentives to reduce carbon emissions (Chen et al., 2022).

However, at the industry level, there is no empirical evidence for the carbon mitigation effect of the ETS yet. And there even seems to be an increase in the carbon emissions of the compliance industries as a whole. Statistical data in Guangdong pilot ETS shows that, in 2021, the carbon emissions of the compliance enterprises reduced by 16% compared to 2013. But during the same period, the total energy consumption of the compliance industries increased by 14.7%[1]. Moreover, compared to 2013, the carbon emissions of the compliance industries increased by 12.3% in 2018[2]. Compared to the non-compliance industries, the carbon emissions of the compliance industries seem to increase significantly after the launch of Guangdong pilot ETS. This phenomenon deviates from the conclusion of some literature that the ETS promotes carbon mitigation at the industry level (Hu et al., 2020).

Given that the ETS encompasses only a fraction of enterprises within key industries and the transmission of carbon price information remains weak, a plausible explanation for the increasing carbon emissions within compliance industries is the phenomenon of intra-industry carbon leakage. This entails a scenario where the reduction in carbon emissions by compliance enterprises is counteracted by a corresponding increase in emissions from non-compliance enterprises within the same industry. One potential mechanism driving this intra-industry carbon leakage is cost crowding-in. Specifically, the additional emission costs incurred by compliance enterprises serve as an incentive for non-compliance entities to ramp up production and emissions, thereby crowding them into the same industry. When the resultant increase in carbon emissions from the cost crowding-in mechanism surpasses the reductions achieved by compliance enterprises, it leads to an overall escalation in carbon emissions within compliance industries.

To test this hypothesis, we adopt Guangdong pilot ETS as a representative sample to empirically test the increase in the carbon emissions of the compliance industries, and theoretically analyze the internal channel for the increased industry-level carbon emissions. Guangdong pilot is chosen for two reasons. First, Guangdong pilot ETS has relatively high price continuity, market volume and degree of marketization, leading to a better quality of market development than that of other regional pilot ETS[3]. Second, Guangdong province has similar industrial structure to China as

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1 Data on total energy consumption by industry are from the Guangdong Statistical Yearbook.

2 As the paper industry was included in the Guangdong pilot ETS as the compliance industry in 2017, the paper industry was not taken into account when calculating the carbon emissions of the compliance industries as a whole.

3 Firstly, the Guangdong pilot ETS has a better mechanism and a longer time of exploration and practice in

a whole. As is well known, manufacturing industries play an important role in Guangdong province, which makes Guangdong's experience in carbon mitigation a useful reference for the national low-carbon transformation. These characteristics render Guangdong pilot ETS very representative and valuable (Wang et al., 2015). Therefore, it is of great significance to examine the effectiveness of Guangdong pilot ETS in reducing carbon emissions, and thoroughly detect the main existing problems in the current design of the ETS. These findings can provide important references for the design and development of all the regional pilot ETS and even the national ETS in China.

Compared with the existing studies, this paper has two marginal contributions. First, we verify the intra-industry carbon leakage in China’s ETS, which unexpectedly results in an increase in the industry-level emissions, in spite of a carbon mitigation in the compliance enterprises in the same industries. This not only expands the literatures about carbon leakage which mainly focus on intra-region leakage, but also provides empirical evidence for the theoretical disussions about intra-industry leakage. Second, we theoretically clarify that the cost crowding-in mechanism accounts for the unexpected results of the ETS. This emphasizes the importance of comprehensive supervision for the ETS and the carbon price efficiency.

The rest of this paper is structured as follows. Section 2 is the literature review. Section 3 presents the research design and empirical findings regarding the industry-level emissions growth effect of the ETS. Section 4 demonstrates the underlying theoretical mechanism of this effect, namely, the cost crowding-in mechanism, and Section 5 concludes with key policy implications.

2. Literature review

2.1. Carbon mitigation effects of the ETS around the world

The design of the ETS originates from Coase's property rights theory, aiming to solve the externality problems of carbon emissions. Mainly adopting the Cap-and-Trade mechanism, the ETS has been considered as a useful market-based tool to reduce carbon emissions (Martin et al., 2014). Previous studies have shown that, although the ETS may lead to short-term retard in economic development while reducing carbon emissions (Segura et al., 2018; Ferrara and Giua, 2022), the negative economic impacts of the ETS are relatively small compared to the other climate policy instruments (Xu et al., 2023).

The European Union took the initiative in launching the Emission Trading Scheme (ETS) in 2005, known as the EU ETS. Since its inception, the EU has spearheaded the global transition towards a low-carbon economy. The EU ETS stands as the most mature ETS currently in operation, with its developmental experience and associated policies serving as crucial benchmarks for other nations worldwide. Consequently, research on the carbon mitigation impact of the EU ETS is abundant.

Numerous studies have demonstrated the efficacy of the EU ETS in reducing carbon emissions (Martin et al., 2016). Initially, at the EU level, the EU ETS faced challenges in achieving substantial emissions reductions due to the transfer of additional emission costs from compliance enterprises

auctioning allocation and the bidding and trading mechanism. The tidal effect in Guangdong pilot ETS is relatively weak, and the enterprises are more active in carbon asset management. Secondly, the Guangdong pilot ETS has relatively high data quality. Data quality is an important foundation for the management and the healthy development of the ETS. The MRV (Monitoring, Reporting and Verification) mechanism in the Guangdong pilot ETS requires the enterprises to formulate a data monitoring plan to ensure the consistency of their carbon emissions data. Thirdly, Guangdong Province is a large and powerful manufacturing province, with total GDP ranking first in the country continuously for 34 years, and the carbon emissions ranking fourth in the country. Then the enterprises have high demands to manage carbon emission costs.

downstream (Anger, 2008). However, as the market gradually matured, the emission reduction potential of the EU ETS began to materialize. Estimates indicate that, during the first phase of the EU ETS, the carbon mitigation effect at the EU level ranged between 2.5% to 5% (Venmans, 2012). Moreover, at the national and regional levels within Europe, countries such as Germany and France have demonstrated notable emission reductions under the EU ETS (Martin et al., 2016). Furthermore, at both the industry (Ellerman and Buchner, 2008) and enterprise levels (Martin et al., 2016; Dechezleprêtre et al., 2023), the carbon mitigation impact of the EU ETS has been observed and confirmed.

In contrast to the EU ETS, the carbon mitigation effectiveness of ETS in other areas has not yet been fully realized, and in some instances, ETS implementation may even result in increased emissions. In the United States, several studies have affirmed the notable carbon mitigation effects achieved by both the RGGI ETS and the California ETS (Murray and Maniloff, 2015; Hernandez-Cortes and Meng, 2023). However, recent research suggests that the U.S. ETS has resulted in firm-level carbon leakage (Hernandez-Cortes and Meng, 2023) and even an uptick in emissions among compliance enterprises, implying a potential overestimation of the U.S. ETS's carbon mitigation impact (Zhou and Huang, 2021). Bartram et al. (2022) analyzed a sample from the California ETS and found evidence of corporate regulatory arbitrage under the Cap-and-Trade mechanism. They observed that compliance enterprises relocated emitting facilities to other regions to evade ETS compliance requirements, while non-compliance enterprises lacked intrinsic incentives to reduce emissions, resulting in a significant overall increase in industry and regional carbon emissions. In Canada, Hanoteau and Talbot (2019) reported that the Quebec ETS effectively reduced carbon emissions among compliance enterprises. In South Korea, Kim and Yu (2018) found that, when carbon prices are low, South Korean enterprises tend to opt for paying penalties for excess emissions rather than reducing emissions to comply with regulatory requirements. Their findings elucidate a common phenomenon in the South Korean ETS, where even a modest trading volume can precipitate a 10% decline in carbon prices.

2.2. Carbon mitigation effects of China's ETS

Since the official launch in 2013, China's ETS has gradually evolved from several regional pilots to a unified national market. The researches on its carbon mitigation effect have mainly focused on the national level, regional level and enterprise level. At the national level, China's ETS effectively reduces the national carbon emissions (Xu et al., 2023). Li and Jia (2016) use the CGE model and find that, China's ETS effectively reduces the national carbon emissions, but it has a greater negative impact on the economic growth in the electric power, non-ferrous metal and some other industries.

At the regional level, studies have shown that regional ETS effectively reduces the carbon emissions not only in pilot provinces but also in cities and even the counties whithin those provinces. Research based on provincial data indicates that the regional pilot ETS promotes green technology innovation (Zhao et al., 2023), enhance energy efficiency (Chen et al., 2021b), and decrease carbon emissions (Zhang et al., 2019b). Similarly, studies using city-level data and county-level data demonstrate that regional pilot ETS reduces carbon emissions in both cities and counties within pilot provinces (Zhang et al., 2020b; Shi et al., 2022).

At the enterprise level, numerous studies find that the ETS promotes enterprise innovation and technological advancement (Jin et al., 2022), particularly in green innovation (Liu and Liu, 2023), and reduce the carbon emissions among compliance enterprises (Chen et al., 2022). However, enterprises in the compliance industries not regulated by the ETS may experience increased emissions. Therefore, further examination is required to determine whether ETS effectively reduces overall industry emissions. In addition, a recent study by Zhu et al. (2022) suggests that China's ETS elevates non-carbon greenhouse gas emissions among compliance enterprises.

Even though there is substantial evidence indicating that China's ETS effectively reduce carbon emissions within pilot regions and among compliance enterprises, limited attention has been given to how the ETS influences carbon emissions at the industry level in China. While some studies suggest that the ETS fosters green innovation and lowers carbon emissions in compliance industries (Zhou et al., 2023), others have been criticized for their methodological biases, such as the misuse of analytical techniques or the conflation of regional and industry effects (Zhang et al., 2019a; Gao et al., 2020; Peng et al., 2021). Consequently, these shortcomings may lead to overestimations or misinterpretations of the ETS's impact on overall industry emissions. Thus, the existing literature has not yet provided a precise assessment of the ETS's effect on industry-level carbon emissions or offered explanations for any potential increases in emissions among compliance industries (Zhang et al., 2019a; Hu et al., 2020).

2.3. ETS and carbon leakage

Under the Kyoto Protocol, countries worldwide have proposed climate policies with varying intensities, leading to concerns about carbon leakage, which can weaken the effectiveness of these policies (Antimiani et al., 2016). With the implementation of ETS in some countries and regions, there has been considerable debate over whether they contribute to carbon leakage. While some studies suggest that the ETS, covering only a portion of the industries and enterprises, does not cause significant carbon leakage (Grubb et al., 2022), most of the literature finds the opposite, undermining the carbon mitigation effects of the ETS (Clò, 2010). The scale of carbon leakage from ETS can be significant. Bauer et al. (2015) measured the carbon leakage rate using various models and settings, finding it to range from -4% to 62%[4]. In an earlier study, Babiker (2005) even suggested a carbon leakage rate as high as 130%.

Moreover, research has delved into the mechanisms behind carbon leakage, with particular attention on the non-energy product trade channel. On the one hand, compliance firms may opt to relocate production and investment to regions with less stringent climate policies (Tiba and Belaid，2020; Yu et al., 2021; Pan and Yu, 2024). On the other hand, changes in the product prices due to increased production costs may erode the competitiveness of compliance firms in product markets, inadvertently incentivizing investment, production and emissions among non-compliance enterprises, thereby resulting in carbon leakage (Holladay et al., 2018).

Existing studies mainly investigate the carbon leakage between countries and regions, and the recent literature has begun to focus on intra-industry carbon leakage. Relevant researches mainly focus on the theoretical possibility and the empirical existance for intra-industry carbon leakage. From the theoretical perspectives, Fowlie (2009) illustrates the potential intra-industry carbon leakage. The incomplete regulation of imperfectly competitive industries where the climate policies restrict the emissions of only some of the high-emitting firms in the industry, can lead to the intra-industry carbon leakage and reduce the effectiveness of climate policies in reducing emissions.

From the empirical perspectives, researches find some evidences for the existance for intra-

[4] A negative carbon leakage rate indicates the existence of reverse carbon leakage or "negative leakage". The non-compliance units (regions/industries/enterprises) have reduced their emissions even though they have not been directly subjected to the regulatory requirements in reducing emissions.

industry carbon leakage. Guo et al. (2020) finds that the country-level carbon mitigation effect of the EUETS mainly comes from the industrial giants, with a significant room for reducing emissions of the small- and medium-sized compliance enterprises, which indicates that intra-industry carbon leakage may take place in the EUETS. Some studies find the intra-region carbon leakage (He et al., 2020; Zhang and Zhao, 2023), but the emitting-firms can hardly transfer into another industry within a region, which verifies the intra-industry carbon leakage from the regional aspect. Some recent studies find that China's ETS induces intra-industry carbon leakage (Zhang et al., 2020a). Under the ETS, the emitting-firms shift their production to the production-affiliated enterprises (He and Chen, 2023) or non-compliance enterprises within the corporation groups (Gibson, 2019; Chen et al., 2021a), so as to avoid the additional emission costs.

However, these studies only focus on the existance for intra-industry carbon leakage, and have not yet empirically examined the consequences associated with the risk of intra-industry carbon leakage. This intra-industry carbon leakage may lead to an increase in the overall emissions of the compliance industries despite a decrease in that of the compliance enterprises, which may be in accord with the situation in Guangdong pilot.

In summary, while substantial body of literature confirms the carbon mitigation effects of ETS for the compliance regions and enterprises. some studies suggest that under certain conditions, ETS may actually increase the carbon emissions for compliance enterprises. Additionally, at the industry level, enterprises not regulated by ETS within compliance industries may increase their carbon emissions, resulting in intra-industry carbon leakage. Therefore, further investigation is needed to determine whether ETS can effectively reduce the industry-level carbon emissions, and to clarify the mechanisms driving the increase in emissions within compliance industries.

3. Research design and empirical findings

3.1. Methodology and data

The ETS has gradually expanded its coverage to include more regulated industries. Therefore, we employ a multi-period DID model to access the effect of the ETS on the industry-level carbon emissions. Consider a benchmark two-way fixed-effects model as in Equation (1):

$$emission_{j,t} = \beta_1 + \beta_2\left(Treat_j \times Post_{j,t}\right) + Control + FE + e_{j,t} \tag{1}$$

where $emission_{j,t}$ denotes the emissions of industry j in year t. Following Zhang et al. (2019a) and other related studies, we use carbon emissions $CO2$ and carbon intensity CII as the proxy for emissions, both of which are logarithmically transformed. $Treat_j$ is the ETS treatment variable, indicating the inclusion of the compliance industries in the ETS. $Post_{j,t}$ is the policy treatment time variable, taking the value of 1 after the industry j being included in the ETS, and 0 otherwise. The fixed effects FE include industry fixed effects and year fixed effects, so as to control the information not included in the model at the industry level and the year level. At this point, the coefficient β_2 measures the policy effect of the ETS on the emissions of the compliance industries (experimental group).

Table 1 Variables description

Variables	Descriptions of Variables
Panel A. Dependent Variables	

Carbon Emissions ($CO2$)	Carbon emissions of the industry in natural logarithm.[a]
Carbon Intensity (CII)	Industry carbon emissions / industry gross industrial output value (current year prices), in natural logarithm.[a,b]
Panel B. Independent Variables	
$Treat_j$	The compliance industries take the value of 1, while non-compliance industries take the value of 0. The compliance industries are power, petrochemical, iron and steel, cement, and paper industry.[c]
$Post_{j,t}$	The value of 1 is taken when the compliance industry is included in the Guangdong pilot ETS, otherwise 0. The paper industry was included in the Guangdong pilot ETS in 2017, while the other compliance industries were included in 2013.[c]
$Treat_j \times Post_{j,t}$	DID term.
Panel C. Control Variables	
Number of enterprises	The number of enterprises in the industry, in natural logarithm.[b]
Asset size	The industry assets in natural logarithm. [b]
Industrial value added	The industrial value added of the industry in natural logarithm. [b]
Export share	The industry export delivery value (current year price) / the industry gross industrial output value (current year price). [b]
Leverage	The industry liabilities / the industry assets. [b]
Current ratio	The industry current liabilities / the industry current assets. [b]

Note: The superscript a means that the data are from CEADs (Carbon Emission Accounts & Datasets). The superscript b means that the data are from Guangdong Industrial Statistics Yearbook. The superscript c means that the data are organized according to the announcements of the Guangdong Provincial Department of Ecology and Environment.

We control for several relevant characteristics, guided by existing literature and data availability. Firstly, we control for industry scale variables (Hu et al., 2020), such as the number of enterprises and industry asset size. Secondly, we include controls for industry development levels (Zhang et al., 2019a; Hu et al., 2020), such as industrial value added and export share. Thirdly, industry risk variables are accounted for (Zhang et al., 2019a), such as the industry leverage ratio and current ratio. All continuous variables are winsorized within the (1%, 99%) interval.

We utilize data spanning from 2000 to 2018 and focus on the Guangdong pilot ETS as our research subject. The Guangdong pilot ETS offers representative and valuable development insights, surpassing other regional pilots in terms of quality. Its experience serves as a crucial reference for enhancing other regional pilot ETS initiatives and potentially the national ETS in China. Our sample period encompasses the entire evolution of China's climate policies, while excluding the impacts of COVID-related shocks on the manufacturing sector. Table 1 provides descriptions of the variables utilized in the analysis.

Table 2 Summary statistics of variables

Variables	Mean	Standard deviation	Minimum	Maximum
$CO2$	13.6859	1.7806	10.4448	19.3874
CII	-4.5126	1.7400	-7.4256	0.4532
Number of enterprises	6.2729	1.5378	0.6931	8.5341
Asset size	18.0852	1.3219	13.4936	21.1080
Industrial value added	16.9874	1.3542	12.4664	19.9973
Export share	0.3409	0.6322	0	4.9532
Leverage	0.5582	0.1008	0.1008	0.9022
Current ratio	1.1910	0.3455	0.1944	4.1717

Note: Sample range from 2000 to 2018. Sample size is 643. Definitions of variables are shown in Table 1.

Table 2 provides a summary of the variable statistics. Notably, there are considerable differences in emissions among various manufacturing industries in Guangdong province. The ratio between the highest and lowest carbon emissions is about $e^{19.3874} \div e^{10.4448} \approx 7650$times, with a similar ratio observed for carbon intensity at $e^{0.4532} \div e^{-7.4256} \approx 2640$ times. Regarding industry scale, there are also significant variations across different industries. In terms of industry development level, all industries in Guangdong province have high production values and export shares. The average industrial value added remains high, with an average export share of around 34%, and some industries reaching as high as 495%. In terms of the industry risk, while manufacturing industries in Guangdong province generally maintain stable growth, some may face potential risks. Certain industries exhibit high leverage ratio of about 90%, while others have a lower current ratio of 19%.

3.2. Empirical results

We adopt Equation (1) to test the effect of the ETS on the carbon emissions of the compliance industries, and Table 3 shows the results. Compared with the non-compliance industries, the ETS significantly increases the carbon emissions and carbon intensities of the compliance industries. The carbon mitigation effect of the ETS at the industry level has not yet appeared. On average, the ETS increases the gap in carbon emissions between the compliance industries and non-compliance industries by about$e^{0.3400} - 1 = 40.5\%$, and it increases the gap in carbon intensities by about $e^{0.3208} - 1 = 37.9\%$. These findings suggest that the ETS has not succeeded in reducing carbon emissions or carbon intensities at the industry level[5]. The industry-level emissions increase, though

[5] Recent research by Zhou et al. (2023) finds that, China pilot ETS has a stronger effect on promoting green innovation in non-compliance industries, compared to compliance industries. This aligns with our findings. Compared to non-compliance industries, the ETS may relatively increase carbon intensities in compliance industries, probably due to a relatively lower green innovation in compliance industries induced by the ETS.

the compliance enterprises in the industry reduce emissions as confirmed by the literature and the statistical data in Guangdong.

Table 3 The effect of Guangdong pilot ETS on industry-level emissions

	(1)	(2)	(3)	(4)
	$CO2$	$CO2$	CII	CII
$Treat \times Post$	0.3125***	0.3400***	0.3868***	0.3208***
	(3.41)	(3.72)	(3.67)	(3.18)
Number of enterprises		-0.1031*		-0.0341
		(-1.67)		(-0.42)
Asset size		0.2135**		-0.0051
		(2.58)		(-0.05)
Industrial value added		-0.0630		-0.9199***
		(-0.83)		(-8.79)
Export share		-0.0153		0.4698***
		(-0.47)		(5.16)
Leverage		0.9886***		1.0100***
		(4.52)		(3.66)
Current ratio		-0.3249***		-0.3525***
		(-3.99)		(-4.21)
Constant	12.0015***	9.9345***	-4.8284***	9.3245***
	(128.54)	(7.93)	(-32.72)	(6.72)
Industry fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
N	643	634	643	634
adj. R^2	0.9547	0.9630	0.8902	0.9481

Note: t-values based on robust standard errors are in parentheses. *, ** and *** denote 10%, 5% and 1% significance levels, respectively.

3.3. Robustness check

We test the robustness of our findings by considering five potential sources of bias. First, since the parallel trend assumption is an important prerequisite for the DID model, we verify the validity of this assumption. Second, to address concerns about the heterogeneity of treatment effects potentially leading to misinterpretations of the ETS policy effects, we conduct a robustness check. Third, the observed increase in industry-level emissions may be influenced by some unobservable factors specific to the Guangdong pilot, so we address this potential endogeneity and also test the generalizability of the ETS-induced emissions increase. Fourth, allowance allocation is a crucial component of the ETS, and its omission could result in endogeneity due to omitted variables. We therefore address this issue and test the moderating effect of allowance allocation. Fifth, the endogeneity arising from reverse causality and emissions continuity may lead to misinterpretations of the ETS policy effects (Shobande et al., 2024), so we also consider these factors in our robustness check.

3.3.1. Parallel trend test

We test the parallel trend assumption using the event study method[6]. The results presented in Figure 1 indicate that, the coefficients before the launch of ETS are insignificant[7], supporting the validity of the parallel trend assumption for industry-level carbon emissions and carbon intensities. However, following the implementation of the ETS, particularly three years after its introduction, there is a significant increase in both industry-level carbon emissions and carbon intensities.

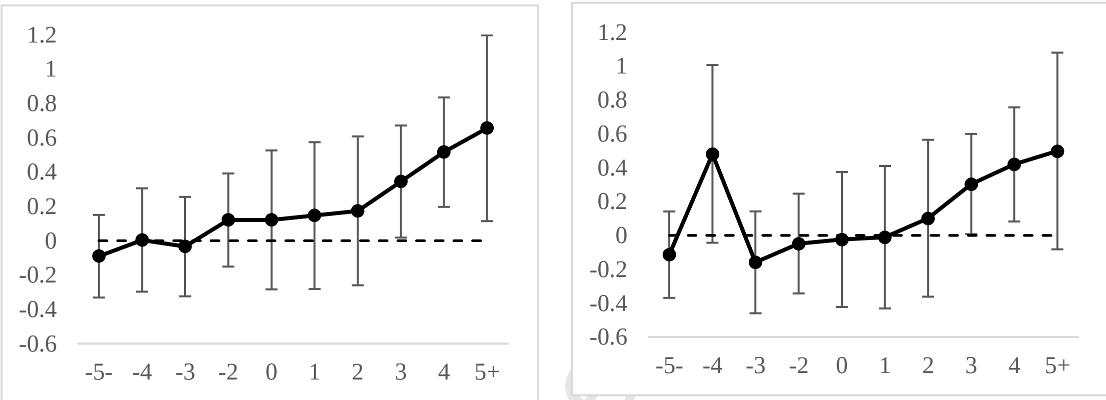

Figure 1 Parallel trend test results of $CO2$ (Left) and CII (right)

Note: Boxes indicate confidence intervals at the 95% level. The benchmark is 1 year before the ETS was launched. Time 0 indicates the point in time when the policy was implemented, -5- indicates 5 and more than 5 years before the ETS was launched, and 5+ indicates 5 and more than 5 years after the ETS was launched.

3.3.2. Heterogeneity of policy effects

We examine the robustness of our findings by considering policy heterogeneity over different time periods. As the ETS gradually incorporates various industries, the heterogeneity of treatment effects may lead to misinterpretations of the ETS policy effects. Recent studies have highlighted the challenge of satisfying the assumption of inter-period homogeneity in practice, suggesting that traditional multi-period DID model estimates may be biased. Moreover, the traditional multi-period DID model only identifies the weighted average effect of the policy at different treatment times, which may misjudge the actual policy effect (Goodman-Bacon, 2021). To address these concerns, we employ the multi-period DID estimator decomposition method proposed by Goodman-Bacon(2021) to decompose and identify the heterogeneous policy effects of the ETS on compliance

6 The regression model is $emission_{j,t} = \beta_1 + \beta_{-5}\left(Treat_j \times Time(-5-)\right) + \sum_{l=-4}^{-2} \beta_l\left(Treat_j \times Time(l)\right) + \sum_{l=0}^{4} \mu_l\left(Treat_j \times Time(l)\right) + \mu_5\left(Treat_j \times Time(5+)\right) + Control + FE + e_{j,t}$. The benchmark is 1 year before the ETS was launched, i.e. Time(-1). Time(0) indicates the point in time when the policy was implemented. Time(-5-) indicates 5 and more than 5 years before the ETS was launched, and Time(5+) indicates 5 and more than 5 years after the ETS was launched.

7 The coefficient of $Treat_j \times Time(-4)$ is insignificant but suddenly jumps up. This suddenly large but insignificant coefficient occurs, because the sudden drop in the industrial value added in Guangdong. In 2009, 4 years before the launch of the ETS, the industrial value added suddenly decreased due to the global financial crisis. The total exports and imports even suffered a negative growth in 2009. In 2010, Guangdong recovered from the crisis. These result in a sudden increase in 2009 in the carbon intensity, calculated by carbon emissions divided by industrial value added.

industries included at different time points. The results are shown in Table 4.

The Goodman-Bacon decomposition results show that the ETS induces a relative increase in carbon emissions across all compliance industry groups, with the first group experiencing a particularly notable increase. Following the ETS launch, both G2013 and G2017 exhibit increased emissions compared to non-compliance industries, with G2013 showing a higher increase than G2017. These findings suggest that, accounting for the heterogeneity of treatment effects, the rise in industry-level carbon emissions induced by the ETS persists. Importantly, these conclusions remain highly robust.

Table 4 Goodman-Bacon decomposition results for two-period DID models

	(1)		(2)	
	$CO2$		CII	
Group Comparison	ratio	weights	ratio	weights
G2013 VS Non-compliance	0.3372	0.8907	0.4688	0.8492
G2017 VS Non-compliance	0.2132	0.0485	0.0822	0.0675
G2013 VS G2017	0.4027	0.0428	-0.4317	0.0405
G2017 VS G2013	-0.2362	0.0180	-2.0237	0.0428
DID estimate	0.3237		0.2996	
Control variables	Yes		Yes	
Industry fixed effects	Yes		Yes	
Year fixed effects	Yes		Yes	

Note: G2013 and G2017 denote the industry groups that were included in Guangdong's pilot ETS in 2013 and 2017, respectively. G2013 vs. G2017 denotes the difference between the two groups after the ETS policy shock in 2013, while G2017 vs. G2013 denotes the difference between the two groups after the ETS policy shock in 2017.

3.3.3. Alternative pilot sample

We test the effect of the ETS on the industry-level carbon emissions adopting the Hubei pilot sample. The effect of Guangdong pilot ETS on the industry-level carbon emissions may be related to certain characteristics of Guangdong province, which may lead to potential endogeneity from missing variables. Moreover, the results of the increased emissions induced by the ETS still need more evidence from other regional pilot in China. To address these concerns, we adopt Hubei pilot sample. This can not only examine the robustness of our findings under Guangdong pilot sample, but also illustrate whether the increased emissions are general in China’s regional pilots.

The Hubei pilot ETS is highly comparable to Guangdong pilot ETS. First, both Hubei and Guangdong share a similar industrial structure, reflecting China's manufacturing-oriented economy. Second, the Hubei pilot ETS includes industries similar to those covered by the Guangdong pilot, primarily focusing on manufacturing, with the Hubei pilot even extending to additional sectors such as automobile manufacturing. Third, the quality of the market development of Hubei and Guangdong pilots is highly comparable in terms of development history, degree of marketization and market trading vitality.

Given these similarities, we adopt the Hubei sample and use Equation (1a) to examine the impact of the ETS on the industry-level carbon emissions in Hubei. The data comes from CEADs database and Hubei Statistical Yearbook. Due to the serious missing value problem, the control variables $ControlHB$ only contain three, including the number of enterprises, gross industrial output value in natural logarithm and the current ratio[8].

$$emission_{j,t} = \beta_1 + \beta_2(Treat_j \times Post_{j,t}) + ControlHB + FE + e_{j,t} \quad (1a)$$

The results are shown in Table 5. The estimated coefficient of the difference-in-difference term is significantly positive. After controlling the industry scale, the estimated coefficient is still positive but not significant. These results suggest that the Hubei pilot ETS also increases industry-level carbon emissions and carbon intensities. Our findings, i.e., ETS induces an increase in emissions of the compliance industries, is highly robust. This provides a useful reference for the future development of the regional pilots as well as the national ETS in China.

Table 5 The effect of Hubei pilot ETS on industry-level emissions

	(1)	(2)	(3)	(4)
	$CO2$	$CO2$	CII	CII
$Treat \times Post$	0.2755**	0.3119***	0.4287***	0.2700**
	(2.47)	(2.83)	(3.29)	(2.26)
Number of enterprises		-0.0489		-0.0077
		(-0.36)		(-0.05)
Gross industrial output value		0.1673**		-0.7525***
		(2.07)		(-7.57)
Current ratio		-0.0077		-0.0388
		(-0.13)		(-0.64)
Constant	10.1500***	7.9654***	-4.2612***	6.6112***
	(26.55)	(6.55)	(-12.64)	(3.87)
Industry fixed effect	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
N	541	541	541	541
adj. R^2	0.9276	0.9279	0.8951	0.9174

Note: t-values based on robust standard errors are in parentheses. *, ** and *** denote 10%, 5% and 1% significance levels, respectively. Gross industrial output value is in natural logarithm.

3.3.4. Endogeneity from allowance allocation

Some researchers have identified a relationship between the ETS's carbon mitigation effect and allowance allocation. Traditionally, it is believed that a high allowance cap increases the supply of emission allowances, which lowers the carbon price and reduces the incentives for enterprises to cut emissions. However, recent research suggests that a decrease in the allowance cap may also diminish enterprises' incentives. Kollenberg and Taschini (2016) find that compliance firms can reduce carbon abatement costs through intertemporal banking and borrowing. With a decreasing

[8] The control variables $ControlHB$ for Hubei sample in equation (1a) are from the control variables $Control$ for Guangdong sample in equation (1). Firstly, several variables are missing before 2005, including asset size, export share and leverage. Secondly, gross industrial output value is used rather than industrial value added, due to the missing values since 2008. The summary statistics of variables for Hubei sample are shown in Appendix B. The regression results for Guangdong sample under $ControlHB$ are shown in Appendix C.

allowance cap, firms may exploit cost arbitrage opportunities to lower abatement costs rather than reduce emissions. Similarly, Fuss et al. (2018) observe that a significant reduction in the allowance cap can lower carbon prices, reduce the intertemporal efficiency of the ETS, and eliminate incentives for enterprises to cut emissions. These studies highlight the importance of flexible adjustments to the allowance cap to prevent potential increases in emissions resulting from intertemporal arbitrage.

Relevant researches imply that, the increased emissions induced by the ETS may be attributed to the allowance allocation. Therefore, we control the allowance allocation and re-estimate the industry-level effect of the ETS. We focus on the effect of allowance allocation on carbon emissions $CO2$[9]. We use Equation (2) to test the moderating effect of allowance cap on the ETS's effect on carbon emissions. Two measures for allowance cap, are used one-by-one in the model[10]:

$$emission_{j,t} = \beta_1 + \beta_2 DID_{j,t} + \beta_3\left(DID_{j,t} \times CAP_t\right) + Control + FE + e_{j,t} \tag{2}$$

where $DID_{j,t} = Treat_j \times Post_{j,t}$. The allowance cap in Guangdong pilot ETS is low and shows a downward trend, as shown in Appendix D. This shows that, Guangdong pilot ETS keeps a strong and gradually strengthened supervision, while carbon emissions of compliance industries keep increasing.

The results in Table 6 show that, allowance cap has a significant negative effect on industry-level carbon emissions. A lower allowance cap leads to a larger increase in compliance industries' carbon emissions induced by the ETS. Under a lower cap, compliance enterprises face higher pressure and decreases more emissions. However, industry-level emissions increase, which shows that decrease in compliance enterprises' emissions is less than increase in emissions of uncovered firms in the same industries.

These results show that, the ETS effectively promotes carbon mitigation in the compliance enterprises of the compliance industries, but fails to reduce the overall carbon emissions of the industries. Moreover, these results imply that intra-industry carbon leakage leads to this pheonomenon.

Table 6 The moderating effect of allowance cap on the ETS's effect on carbon emissions

	(1) $CO2$	(2) CII
$Treat \times Post$	4.5259**	3.9630*
	(2.33)	(1.90)
$Treat \times Post \times CAP1$	-1.1e+08**	
	(-2.16)	
$Treat \times Post \times CAP2$		-6.8e+07*
		(-1.74)
Number of enterprises	-0.0924	-0.0962
	(-1.52)	(-1.58)
Asset size	0.2023**	0.2095**

9 Traditional view holds that allowance cap is correlated with change in carbon emissions, but irrelevant with change in carbon intensities.

10 We consider two measures for allowance cap, $CAP1$ and $CAP2$. $CAP1$ is the allowance cap amount divided by total carbon emissions in Guangdong. $CAP2$ is the allowance cap amount divided by total carbon emissions of compliance industries in Guangdong.

	(2.44)	(2.53)
Industrial value added	-0.0592	-0.0635
	(-0.78)	(-0.84)
Export share	-0.0158	-0.0150
	(-0.49)	(-0.46)
Leverage	1.0129***	0.9899***
	(4.61)	(4.52)
Current ratio	-0.3285***	-0.3314***
	(-3.97)	(-4.00)
Constant	9.9959***	9.9791***
	(8.09)	(8.02)
Industry fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
N	634	634
adj. R^2	0.9635	0.9633

Note: t-values based on robust standard errors are in parentheses. *, ** and *** denote 10%, 5% and 1% significance levels, respectively. $CAP1$ is the allowance cap amount divided by total carbon emissions in Guangdong. $CAP2$ is the allowance cap amount divided by total carbon emissions of compliance industries in Guangdong.

3.3.5. Other endogeneity concerns

We test the effect of the ETS on the industry-level carbon emissions taking the endogeneity into account. Recent researches find that, the endogeneity of the carbon mitigation effects of the ETS arises from the reverse causality and emitting continuity. On the one hand, the industries or enterprises with high emissions will be regulated by the ETS, which may lead to the reverse causality. On the other hand, after regulated by the ETS, the enterprises need time to adjust their production and emissions, which may lead to the emitting continuity. The system GMM model is used to address these two types of endogeneity (Shobande et al., 2024). We estimate the system GMM model as in Equation (3):

$$emission_{j,t} = \beta_1 + \beta_2(Treat_j \times Post_{j,t}) + \beta_3 emission_{j,t-1} + Control + FE + e_{j,t} \tag{3}$$

The results in Table 7 show that, after addressing the endogeneity, the increased industry-level emissions by the ETS still exists. There is significant continuity in the industry-level emissions. After addressing the endogeneity from the reverse causality and emitting continuity, the coefficients of the $Treat \times Post$ are still significant. The ETS may increase the emissions of the industry though it decreases the emissions of the compliance enterprises in the same industry. This illustrates the robustness for our conclusions.

Table 7 System GMM results for the effect of Guangdong ETS on industry-level emissions

	(1)	(2)
	$CO2$	CII
$Treat \times Post$	0.1196**	0.3730**
	(2.38)	(2.66)
$L.CO2$	0.9593***	
	(62.18)	

$L.CII$		0.8315***
		(18.59)
Number of enterprises	-0.0252**	-0.0762**
	(-2.68)	(-2.30)
Asset size	0.0190	0.2719**
	(0.67)	(2.07)
Industrial value added	0.0462*	-0.2793**
	(1.77)	(-2.42)
Export share	-0.0453	0.3266***
	(-1.22)	(3.46)
Leverage	0.3651**	0.1406
	(2.15)	(0.39)
Current ratio	-0.0567	-0.2703***
	(-1.22)	(-2.83)
Constant	-0.6759**	-0.5533
	(-2.30)	(-0.68)
Industry fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
N	634	634
AR(2) stat	0.7099	1.1775
	[0.4778]	[0.2390]
Hansen J stat	10.1969	6.6344
	[1.0000]	[1.0000]
F stat	3331***	1518***
	[0.0000]	[0.0000]

Note: t-values based on robust standard errors are in parentheses. *AR(2) stat* are the statistics for the second-order Arellano-Bond serial correlation test, and the null hypothesis is that there is no second-order serial correlation. *Hansen J stat* are the statistics for the over-identification test, and the null hypothesis is that there is no over-identification. *F stat* are the statistics for the joint significance test, indicating the goodness of fit for the model. The p-values for the statistics are in the brackets. *, ** and *** denote 10%, 5% and 1% significance levels, respectively.

4. Mechanisms analysis

The empirical results above have shown that, the Guangdong pilot ETS increases the carbon emissions of the compliance industries. In contrary, as shown in a large number of studies, Guangdong pilot ETS significantly reduces the carbon emissions of the compliance enterprises (Shen et al., 2020). This means that, the ETS effectively promotes carbon mitigation in the compliance enterprises of the compliance industries, but fails to reduce the overall carbon emissions of the industries.

In this section, we theoretically analyze under what conditions this phenomenon may occur, and how to prevent the increase in industry-level emissions. We focus on firm-level and industry-level emissions at the same time, and compare the changes in them with and without ETS. We further analyze the factors leading to this phenomenon by numerical simulation and typical facts.

We focus on two main factors, ETS coverage ratio and market competitiveness[11]. Through these, the inherent mechanism can be verified by the theoretical analysis and case study.

4.1. Model setup

Following related studies such as Zhou et al. (2019), we use the Stackelberg quantity leadership model to analyze the phenomenon above and its inherent mechanism. Particularly, we introduce carbon emissions into the model and compare the changes in the carbon emissions as well as other variables under the ETS, and those without ETS.

4.1.1. Stackelberg model without ETS

First, consider the Stackelberg model without ETS. Assume that there are two types of enterprises in a high-emitting industry. One is the enterprise with high carbon emitting enterprise, and the other is the low-emitting enterprise. The ETS regulates the high-emitting enterprises in the high-emitting industry, but does not regulate the low-emitting enterprises in the same industry. After the launch of the ETS, the high-emitting industry is regulated by the ETS and is categorized as a compliance industry. The high-emitting enterprises in the industry are categorized as compliance enterprises, while the low-emitting enterprises are called as non-compliance enterprises or uncovered enterprises. In general, the more products an enterprise produces, the higher carbon emissions it exhausts. The compliance enterprises are mainly the large-scale enterprises in the industry, which often occupy high market shares in terms of production and sales. Therefore, it is assumed that there is only one representative compliance firm in the high-emitting industry (the compliance industry after the launch of the ETS), which is the leader of the industry and is labeled as Firm 1. There is a measure-one of continuum identical non-compliance firm in the industry, all of which are followers, aggregated and labeled as Firm 2.

Assume the market has heterogeneous preferences. Following Raff and Schmitt (2007), it is assumed that the market demand is $P = a - b(q_1 + \varepsilon q_2)$, where q_1 and q_2 are the outputs of the compliance firm and the uncovered firm, respectively. It is assumed that the ETS coverage ratio of the enterprises in the industry is $\lambda(\varepsilon) \in [0,1]$. Assume $\lambda'(\varepsilon) > 0$, i.e., the ETS coverage ratio is monotonically increasing with respect to the parameterε. The $\varepsilon > 0$ denotes the degree of non-substitutability of the products of the compliance firm. The higher ε is, the utility generated by one unit of the product of the compliance firm to the consumer at the same price level needs to be replaced by more units of the product of the uncovered firm. Since the market share of the compliance firm is relatively large, the ETS coverage ratio $\lambda(\varepsilon)$ is high.

We assume that firms only make output decisions and do not consider green technology innovation decisions[12]. After the compliance firm sets its initial production quantity, the uncovered firm determines its production quantity to capture surplus market demand, which the compliance firm can observe, allowing for subsequent production quantity adjustments. In the absence of an ETS, firms' decision-making processes are unaffected by carbon emissions generated from production activities. All firm-related variables, including production, profits, and emissions, are denoted by *N* under this condition. The profit functions for the compliance and uncovered firms are represented as follows: $\pi_1^N = Pq_1^N - c_1 q_1^N$, and $\pi_2^N = Pq_2^N - c_1 q_2^N$. Equilibrium productions and

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[11] ETS coverage and allowance allocation are important policies in the ETS system. Allowance allocation has significant impact on industry-level emissions, as shown in section 3.3.4. Allowance allocation is highly related to market competitiveness.

[12] Relevant literature confirms that the carbon emissions mitigation by Chinese firms still mainly come from the reduction in product output rather than the improvement in green technology (Zhang and Duan, 2020; Cao et al., 2021).

profits for both firm types are determined by Equations (4-7), while the resulting market share of the compliance firm is governed by Equation (8):

$$\hat{q}_1^N = \frac{a-2c_1+c_2}{2b} \tag{4}$$

$$\hat{q}_2^N = \frac{a+2c_1-3c_2}{4b\varepsilon} \tag{5}$$

$$\hat{\pi}_1^N = \frac{(a-2c_1-c_2)(a-2c_1+c_2)}{8b} \tag{6}$$

$$\hat{\pi}_2^N = \frac{(a-2c_1-3c_2)(a+2c_1-3c_2)}{16b\varepsilon} \tag{7}$$

$$\hat{\lambda}^N = \frac{\hat{q}_1^N}{\hat{q}_1^N+\hat{q}_2^N} = \frac{1}{1+\frac{1}{2\varepsilon}\frac{a+2c_1-3c_2}{a-2c_1+c_2}} \tag{8}$$

Obviously, in equilibrium, the market share of compliance firm $\hat{\lambda}^N(\varepsilon)$ is a monotonically increasing function on the non-substitutability coefficient ε. When $\varepsilon \to \infty$, the market demand is not affected by the production quantity of the uncovered firm, then the products of the compliance firm are completely non-substitutable. In this situation, the consumers have a rigid demand preference for the products of the compliance firm, and the market share of the compliance firm reaches 100%. All the productions in the industry and their carbon emissions will be regulated by the ETS, i.e., the ETS coverage ratio reaches 100%. As the non-substitutability factor ε decreases, the extent to which the market demand influenced by the production quantity of the uncovered firm increases, and the market share of compliance firm decreases. Then the proportion of regulated productions decreases, i.e., the ETS coverage ratio decreases. Therefore, the non-substitutability coefficient ε implies the ETS coverage ratio, i.e., proportion of firms in the industry covered by the ETS.

As shown in the ETS government documents about the emission data verification, emission allowances allocation and clearing in China[13], it is assumed that the carbon emissions e are the product of emission intensity (also called emission coefficient) and productions. Denote the emission intensities of compliance firm and uncovered firm as μ_1 and μ_2, respectively, then the equilibrium emissions of two firms under no ETS follow Equations (9~10). The overall emission of the industry follows Equation (11):

$$\hat{e}_1^N = \frac{a-2c_1+c_2}{2b}\mu_1 \tag{9}$$

$$\hat{e}_2^N = \frac{a+2c_1-3c_2}{4b\varepsilon}\mu_2$$

[13] Both the national ETS and the regional pilot ETS require that, the amounts of allowances to be cleared equals to the verified emissions of the enterprises. The guidelines issued by the Ministry of Ecology and Environment require that, an enterprise's emissions are equal to the emission intensity multiplied by the amounts of products produced, or equal to the emission intensity multiplied by the amount of fossil energy burned.

(10)

$$\hat{e}^N = \frac{a-2c_1+c_2}{2b}\mu_1 + \frac{a+2c_1-3c_2}{4b\varepsilon}\mu_2 \tag{11}$$

4.1.2. Stackelberg model with ETS

Next, consider the Stackelberg model when there is ETS, where the relevant indicators are labeled with Y. The ETS adopts the Cap-and-Trade mechanism. Under this mechanism, the regulator determines the list of compliance enterprises and their allowance allocation in the middle of the year t, and then the compliance enterprises start to estimate their emissions for the current year and carry out the trading of emission allowance. In the first half of the year $t+1$, the emissions of the compliance enterprises during year t will be verified by the regulator, and the enterprises will be forced to fulfill the allowance clearing. Within the compliance industries, the compliance enterprises are required to purchase the emission allowances for their excess emissions out of the allocated amounts of allowances in order to fulfill compliance, and thus need to pay additional costs for their excess emissions. The uncovered enterprises do not need to pay additional costs. Therefore, we assume that the profit functions of the compliance firm follow Equations (12):

$$\pi_1^Y = Pq_1^Y - c_1q_1^Y - p^e(e_1^Y, e_0) * (e_1^Y - e_0) \tag{12}$$

where e_0 is the allowance allocated to the compliance firm, and $p^e(e_1^Y, e_0)$ is the market price for the emission allowances, i.e., the carbon price. The carbon price is the equilibrium price formed by market transactions, driven by the demand and supply of carbon allowances in the market. Therefore, it is assumed that the carbon price is a function of the emissions of the compliance firm and the amounts of allowance allocation, i.e., $p^e(e_1^Y, e_0)$. Assume that the carbon price rises as emissions increase due to the increasing demand, i.e., $\partial p^e/\partial e_1^Y > 0$. Likewise, assume that the carbon price rises as the allocation of allowances decreases due to the decreasing supply, i.e., $\partial p^e/\partial e_0 < 0$. Without loss of generality, assume that the carbon price obeys a linear functional $p^e(e_1^Y, e_0) = ge_1^Y - he_0$, where $g > 0$ denotes the sensitivity of the carbon price to the emissions of the compliance enterprises, and $h > 0$ denotes the sensitivity of carbon price to the amounts of allowance allocation.

If we set g as a constant, then h denotes the relative sensitivity of carbon price to the allowance allocation. The larger the h is, the smaller the impact of carbon emissions of the compliance enterprises on the carbon price is, and the weaker the ability of the carbon price to reflect the demand for emission allowances of enterprises. Consider an extreme situation where h is far greater than g. The carbon price tends to be constant after the allowance allocation is set, and it can hardly be influenced by enterprises' emissions. Therefore, under a constant g, parameter h can indicate the ETS market competitiveness. The larger the h is, the weaker the market competitiveness is[14].

The ETS adopts two main ways in allowances allocation, namely the free allocation and auction allocation, and the free allocation mechanism is currently mainly adopted in China. Two methods are common in the context of free allocation of allowances: grandparenting and benchmarking. Existing literature argues that the grandparenting method raises the incentive for the compliance enterprises to increase emissions in order to obtain more free allowances, and the benchmarking method more effectively constrains the emissions (De Perthuis and Trotignon, 2014).

[14] The ETS market competitiveness may be an important aspect for pricing efficiency. An increase in market competitiveness can improve carbon pricing efficiency. An increase in the h, i.e. a weakened ETS market competitiveness, may weaken carbon pricing efficiency.

In practice, the free allocation based on the grandparenting method has been largely replaced by the benchmarking method for industries with high-quality emission monitoring data. Therefore, we conduct a study under the basic setting of the benchmarking method to examine whether the ETS can effectively constrain the overall carbon emissions of the compliance industries under a more binding regulatory mechanism.

Under the benchmarking method, the compliance firm's allocated allowances e_0 is the product of the benchmark emission intensity μ_0 set by the regulator and the firm production. Generally speaking, the regulator sets a relatively low benchmark according to the emission situation of the whole industry, aiming at encouraging the advanced and penalizing the laggards. Therefore, it is assumed that the benchmark emission intensity μ_0 is the third quartile of the emission intensities within the industry, then $e_0 = \mu_0 q_1^Y = (\mu_1 + \mu_2) q_1^Y / 3$. Under this circumstance, the profit function of the compliance firm follows Equation (12a):

$$\pi_1^Y = Pq_1^Y - c_1 q_1^Y - p^e(e_1^Y, e_0) * (e_1^Y - e_0)$$

$$= Pq_1^Y - c_1 q_1^Y - \left[g\mu_1 q_1^Y - \frac{h(\mu_1+\mu_2)}{3} q_1^Y\right] \frac{2\mu_1 - \mu_2}{3} q_1^Y \tag{12a}$$

The uncovered firm has no emission reduction compliance obligations, does not receive allowances allocated and does not pay additional costs for emissions, so their profit function follows Equation (13). The compliance enterprises are mainly large and high-emitting enterprises, and often need to purchase allowances from the market to meet the compliance requirements. Assume that $e_1^Y > e_0$ and $\mu_1 > \mu_2/2$.

$$\pi_2^Y = Pq_2^Y - c_1 q_2^Y \tag{13}$$

Preliminarily, under the ETS, the compliance enterprises can maximize their profits by reducing the additional emissions costs through carbon mitigation, and they can also do this through moving their productions to some uncovered enterprises. Due to the giant groups in the compliance industries, under the ETS only including high-emitting enterprises with a low coverage ratio, there is a feasibility for the giant groups to transfer high-emitting product lines from their compliance subsidiary enterprises to their uncovered subsidiary enterprises (Gibson, 2019; Chen et al., 2021a).

Equation (12a) and Equation (13) constitute the Stackelberg quantity leadership model under the ETS, and the equilibrium productions and profits follow Equations (14~17):

$$\hat{q}_1^Y = \frac{a-2c_1+c_2}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3} - \frac{\mu_2}{3}\right)} \tag{14}$$

$$\hat{q}_2^Y = \frac{a - c_2 - \frac{b(a-2c_1+c_2)}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3} - \frac{\mu_2}{3}\right)}}{2b\varepsilon} \tag{15}$$

$$\hat{\pi}_1^Y = \frac{z_2\left(a - 2c_1 + c_2 - b\frac{z_2}{z_1}\right)}{2z_1} + \frac{z_2\left(\frac{2\mu_1}{3} - \frac{\mu_2}{3}\right)\left[\frac{z_2 h(\mu_1+\mu_2)}{3z_1} - g\mu_1 \frac{z_2}{z_1}\right]}{z_1} \tag{16}$$

$$\hat{\pi}_2^Y = \frac{(z_3)^2}{4b\varepsilon} \tag{17}$$

where $z_1 = b + 2\left(\frac{2\mu_1}{3} - \frac{\mu_2}{3}\right)\left[g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right]$, $z_2 = \frac{a}{2} - c_1 + \frac{c_2}{2}$, $z_3 = c_2 - a + b\frac{z_2}{z_1}$. Under the ETS, the equilibrium emissions of the compliance firm and the uncovered firm follow Equations (18~19), and the overall emissions of the compliance industry follows Equation (20):

$$\hat{e}_1^Y = \frac{a-2c_1+c_2}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3} - \frac{\mu_2}{3}\right)} \mu_1 \tag{18}$$

$$\hat{e}_2^Y = \frac{a - c_2 - b\frac{a-2c_1+c_2}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3}-\frac{\mu_2}{3}\right)}}{2b\varepsilon}\mu_2 \tag{19}$$

$$\hat{e}^Y = \hat{e}_1^Y + \hat{e}_2^Y \tag{20}$$

The change in the industry-level emissions between the cases under the ETS and that under no ETS follows Equations (21~23):

$$\Delta\hat{e}_1 = \hat{e}_1^Y - \hat{e}_1^N = \mu_1\left[\frac{a-2c_1+c_2}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3}-\frac{\mu_2}{3}\right)} - \frac{a-2c_1+c_2}{2b}\right] \tag{21}$$

$$\Delta\hat{e}_2 = \hat{e}_2^Y - \hat{e}_2^N = -\frac{\mu_2}{2\varepsilon}\left[\frac{a-2c_1+c_2}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3}-\frac{\mu_2}{3}\right)} - \frac{a-2c_1+c_2}{2b}\right] \tag{22}$$

$$\Delta\hat{e} = \hat{e}^Y - \hat{e}^N = \left[\frac{a-2c_1+c_2}{2b+4\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3}-\frac{\mu_2}{3}\right)} - \frac{a-2c_1+c_2}{2b}\right]\left(\mu_1 - \frac{\mu_2}{2\varepsilon}\right) \tag{23}$$

4.1.3. Conditions for firm-level and industry-level carbon mitigation

Firstly, examine the change in emissions of the compliance firm after the launch of the ETS. When $\left(g\mu_1 - \frac{h(\mu_1+\mu_2)}{3}\right)\left(\frac{2\mu_1}{3} - \frac{\mu_2}{3}\right) > 0$, i.e., $\mu_1 > \frac{h}{3g-h}\mu_2 = \frac{1}{3\frac{g}{h}-1}\mu_2$, $\frac{g}{h} > \frac{1}{3}$ and $\mu_1 > \frac{1}{2}\mu_2$ hold at the same time, then $\hat{e}_1^Y < \hat{e}_1^N$, indicating a decrease in the emissions of the compliance firm after the launch of the ETS. Moreover, when $g > h$, these three conditions can be summarized as one condition $\mu_1 > \frac{1}{2}\mu_2$. When these three conditions are satisfied at the same time, compared with the case of no ETS, the emissions of the compliance firm will be reduced when there is ETS. This suggests that the effectiveness of the ETS in constraining the emissions of the compliance enterprises depends on two necessary conditions.

As for the first condition, the carbon price needs to be more sensitive to the changes in demand for carbon allowances, and more sensitive to the amounts of allowances allocated. This emphasizes the competitiveness of the emission trading market, incentivizing the compliance enterprises to actively participate in the market, improving market vitality, and strengthening the ability of the carbon price to reflect the demand for emission allowances. Though the participation of the non-compliance enterprises or investment institutions in the emission trading market especially the spot market helps to improve market liquidity and vitality, it is difficult to promote the carbon price to better reflect the demand for carbon allowances by the compliance enterprises. Therefore, the spot market should be mainly participated by the compliance enterprises. The enthusiasm of the compliance enterprises in emission trading is one of the necessary conditions for the ETS to effectively achieve carbon mitigation.

As for the second condition, the emission intensity of the uncovered enterprises should not be too high, i.e., enterprises with high emission intensity should be included in the ETS for regulation. Compared to the compliance enterprises, some uncovered enterprises may have significantly higher emission intensities but lower productions. These uncovered enterprises are not regulated by the ETS due to their low emissions. However, the high emission intensity of these uncovered enterprises leads to high benchmark emission intensity μ_0 and large amounts of allowance allocation to the compliance enterprises. Then the compliance enterprises may increase their emissions.

This means that the inclusion of enterprises with high standards for supervision is an important bottom line for the effective carbon mitigation among the compliance enterprises. The enterprises with high emission intensities and low productions are prone to become the runaway of the inclusion standard, which reduces the incentives of carbon mitigation for the regulated compliance enterprises. The ETS should emphasize more on the emission intensities of the enterprises rather than the emissions only, and comprehensively monitor the emission intensities and emissions of the enterprises in the industry.

Secondly, examine the change in the emissions of the uncovered firm after the launch of the ETS. Obviously, when the compliance firm reduces emissions, the uncovered firm is bound to increase emissions, indicating a cost crowding-in mechanism. Since the compliance enterprises need to pay additional emission costs, the compliance enterprises may reduce emissions. However, the additional costs will inevitably lead to the cost advantages of the uncovered enterprises in disguise and the resulting expansions in production, which will increase the emissions of the uncovered enterprises. This illustrates that the cost crowding-in mechanism always exists, whereby the additional emission costs of the compliance enterprises will be crowded into the uncovered enterprises, creating a disguised incentive for the uncovered enterprises to produce more and emit more.

Finally, examine the change in the overall emissions of the industry after the launch of the ETS. When$\mu_1 < \mu_2/(2\varepsilon)$, the degree of the increase in emissions of the cost crowding-in mechanism is greater than the degree of the reduction in emissions of the compliance enterprises, then the carbon mitigation of the compliance enterprises is accompanied by the increase of the overall emissions of the whole industry. The degree of the increase in emissions of the cost crowding-in mechanism is not only related to the emission intensities of enterprises, but also directly related to the ETS coverage ratio of the industry $\lambda(\varepsilon)$. The higher the ETS coverage ratio $\lambda(\varepsilon)$ is, the greater the non-substitutability of products of the compliance enterprises ε is, then the greater possibility that the degree of carbon mitigation of the compliance enterprises will be greater than the degree of increase in emissions of the cost crowding-in mechanism, i.e., $\mu_1 \geq \mu_2/(2\varepsilon)$. If the ETS coverage ratio $\lambda(\varepsilon)$ is low, the non-substitutability of products of compliance enterprises ε is weak. The products of the compliance enterprises are easy to be substituted by that of the uncovered enterprises, which may lead to an increase in overall emissions of the industry though a carbon mitigation in the compliance enterprises.

4.2. Numerical simulation

The theoretical analysis above shows that, the increased industry-level emissions result from the great increase in the emissions of uncovered firm within the same industry. In this section, we investigate the evidences for this cost crowding-in mechanism through numerical simulation.

4.2.1. Parameter settings

For market demand, we assume that $a = 100$ and $b = 1$, then the market demand follows $P = a - b(q_1 + \varepsilon q_2) = 100 - (q_1 + \varepsilon q_2)$. For the market supply, we assume that $c_1 = c_2 = 10$, then the production costs of two firms are the same.

Equations (21~23) illustrate that compared to the case of no ETS, the changes in the emissions of the uncovered firms as well as that of the industry after the launch of the ETS are mainly influenced by five parameters, including $\varepsilon, g, h,$ μ_1 and μ_2. Without loss of generality, we assume that $g = 1$, and we adjust the values of four remaining parameters to examine the changes in the emissions and other indicators.

Specifically, we first set the parameters h. As shown in the theoretical model, the carbon price directly affects the profits and productions of the compliance firm. Under the setting $g = 1$, the parameter h has an important impact on the carbon price, indicating the relative sensitivity of the carbon price with respect to the amounts of allowance allocation. Since $\frac{g}{h} > \frac{1}{3}$ is one of the necessary conditions for the carbon mitigation of the compliance enterprises, we examine the changes in the emissions under three cases, $h = 1$, $h = 1.5$ and $h = 2$, respectively.

Then we set the parameter ε. Under the above values of parameters (a, c_1, c_2), the market share of the compliance firm before the launch of the ETS is $\hat{\lambda}^N = 1 - 1/(1 + 2\varepsilon)$. When the market demand and the production costs are given, the market share of the compliance firm is determined by the degree of non-substitutability of its products. The parameter ε indicates the degree of non-substitutability of products of the compliance firm, reflecting the ETS coverage, and it directly affects the change of the overall emission level of the industry $\Delta\hat{e}$. We set the value of parameter ε step by step in the interval of 0.2~1.8 with the step size of 0.2. As the parameter ε increases, the ETS coverage ratio increases.

Table 8 Numerical simulation parameter settings

Parameters	Illustrations	Values
a	Intercept of the market demand function for the industry	100
b	Slope of the market demand function for the industry	1
c_1	Production cost of the compliance firm	10
c_2	Production cost of the uncovered firm	10
g	Sensitivity of the carbon price to the emissions of the compliance firm	1
h	Sensitivity of the carbon price to the allowance allocation of the compliance firm	Set the value one by one in the $[1,2]$ interval with a step of 0.5
ε	Degree of non-substitutability of products of the compliance firm, reflecting the ETS coverage ratio	Set the value one by one in the $[0.2,1.8]$ interval with a step of 0.2
μ_1	Emission intensity of the compliance firm	Set the value one by one in the $[0.5,1]$ interval with a step of 0.02
μ_2	Emission intensity of the uncovered firm	Set the value one by one in the $[0,1]$ interval with a step of 0.02

Under each combination of the values of h and ε, we set the (μ_1, μ_2) combinations. The emission intensities of two firms not only directly affect their emissions, but also influence the profits and productions of the compliance firm through the allowance allocation and carbon price. We set the value of parameter μ_1 in the interval of 0.5~1 and parameter μ_2 between 0~1[15], respectively, step by step with the step size of 0.02. Then we get 26×51 combinations for the

[15] The emission intensities of various industries from the CPCD database show that, most of the compliance industries have an emission intensity less than 1, i.e. less than 1 ton of CO_2 equivalent will be emitted per ton of products. Moreover, according to the guidelines in Guangdong pilot ETS, the benchmarking values of the emission intensities are mostly less than 1.

parameters (μ_1, μ_2). In total, we get 3×9×26×51 combinations for the parameters $(h, \varepsilon, \mu_1, \mu_2)$, as shown in Table 8.

Under the parameter settings and the combinations of parameters $(h, \varepsilon, \mu_1, \mu_2)$ above, we investigate the change in the emissions of the compliance firm, uncovered firm and the whole industry after the launch of the ETS. Furthermore, we examine the necessary conditions for the ETS to effectively reduce the overall emissions of the whole industry.

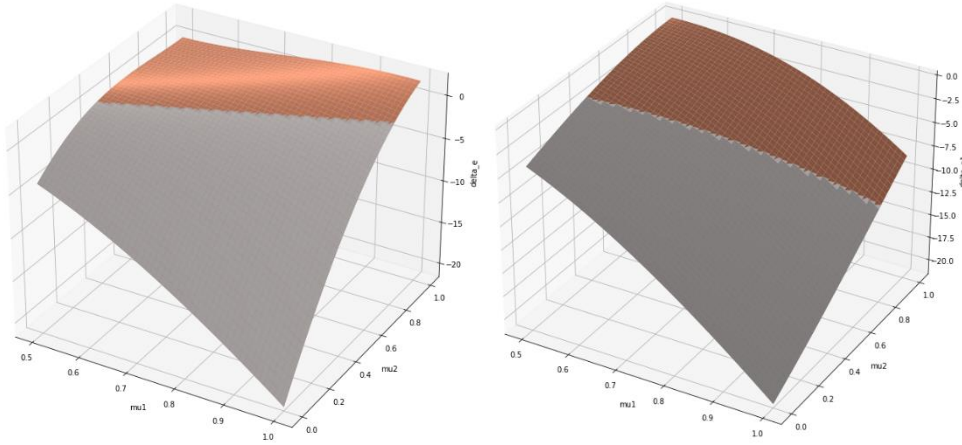
4.2.2. ETS coverage ratio and cost crowding-in

First, under a certain h, we examine the emissions under different combinations of the parameters $(\varepsilon, \mu_1, \mu_2)$. Figure 2 shows the effect of the parameter combinations on the emissions at $h = 1$. The results show that, when $\varepsilon < 1$, i.e., when the market share of the compliance firm before the launch of the ETS $\hat{\lambda}^N < 66.7\%$, there may be $\Delta\hat{e}_1 < 0$ and $\Delta\hat{e} > 0$ simultaneously, indicating an increase in the overall emissions of the industry despite the carbon mitigation of the compliance firm.

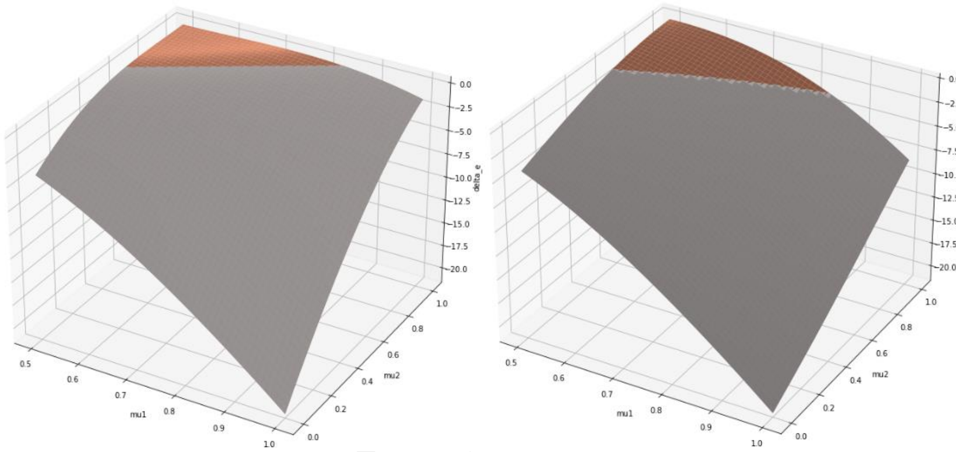
When $h = 1$, under any combination $(\varepsilon, \mu_1, \mu_2)$, the $\Delta\hat{e}_1 < 0$ always holds, indicating that the compliance firm is bound to reduce their emissions. However, when $\varepsilon < 1$, there are some combinations (μ_1, μ_2) satisfying the condition $\mu_1 > \mu_2/(2\varepsilon)$, leading to a higher degree of increase in emissions of the cost crowding-in mechanism than the degree of carbon mitigation of the compliance firm, which results in an increase in the overall emissions of the industry. With the parameter ε increases, the combinations (μ_1, μ_2) that lead to an increase in the overall emissions of the industry, will decline. When $\varepsilon \geq 1$, the market share of the compliance firm $\hat{\lambda}^N \geq 66.7\%$, under any combination $(\varepsilon, \mu_1, \mu_2)$, the carbon mitigation of the compliance firm will be accompanied with the carbon mitigation of the whole industry.

Under the certain h and ε, when μ_1 is high, then a relatively high μ_2 may lead to an increase in the emissions of whole industry though the carbon mitigation of the compliance firm. Take $h = 1$ and $\varepsilon = 0.4$ ($\hat{\lambda}^N = 44.4\%$) as an example. When $\mu_1 = 0.5$, $\mu_2 \geq 0.4$ will lead to the phenomenon above. When $\mu_1 = 0.7$ or $\mu_1 = 0.9$, it is necessary to satisfy $\mu_2 \geq 0.56$ or $\mu_2 \geq 0.72$, respectively, resulting in the phenomenon above.

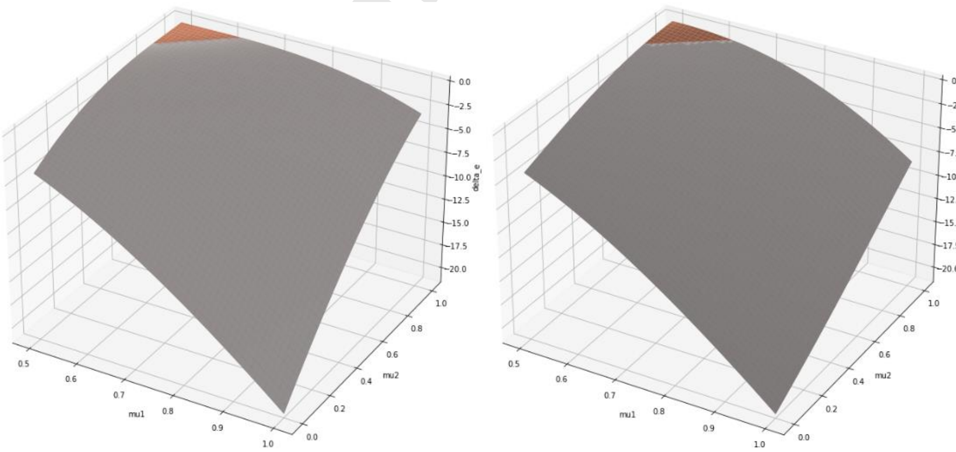
On the one hand, when the emission intensity of the compliance enterprises regulated by the ETS is high, in order to give full play to the carbon mitigation effect of the ETS, the non-compliance enterprises in the industry with emission intensities below a certain level can be excluded from the supervision. This means that, at the initial stage of the launch of the ETS, if only the enterprises with extremely high emission intensities are included in the regulation, then it is only necessary to monitor the emission intensities of all enterprises in the industry and further include the enterprises with emission intensities exceeding a certain level into the regulation, in order to ensure that the ETS can effectively reduce the carbon emissions of the whole industry.



(a) $\hat{\lambda}^N = 44.4\%$ $(\varepsilon = 0.4)$



(b) $\hat{\lambda}^N = 54.5\%$ $(\varepsilon = 0.6)$



(c) $\hat{\lambda}^N = 61.5\%$ $(\varepsilon = 0.8)$

Figure 2 Results for $\Delta\hat{e}$ (left) and $\Delta\hat{e}_1$ (right) under different combinations $(\varepsilon, \mu_1, \mu_2)$ when $h = 1$

Note: Orange areas indicate the combinations(μ_1, μ_2) leading to an increase in the overall emissions of the industry $\Delta\hat{e} > 0$.The X-axis indicates the value of μ_1, the Y-axis indicates thevalue of μ_2, and the Z-axis indicates the value of $\Delta\hat{e}$(left) and $\Delta\hat{e}_1$ (right).

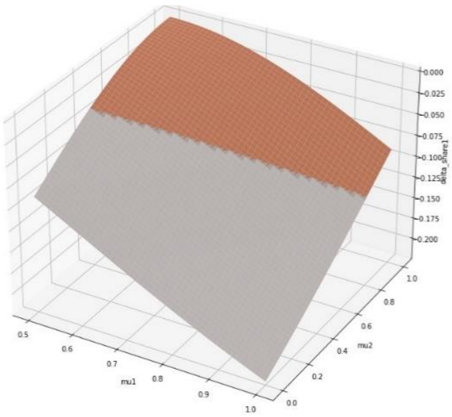
On the other hand, with the decrease in the emission intensities of the compliance enterprises, the emission intensities of the uncovered enterprises need to be reduced synchronously, in order to ensure that the ETS continues to reduce industry-level emissions. This means that, the ETS should establish a dynamic regulatory mechanism to enhance the coverage in the industry, including the previously uncovered enterprises into the regulation when the emissions, especially the emission intensities, of the compliance enterprises are reduced. Gradually expansion of regulated enterprises in the industry will promote the continuous carbon mitigation of the whole industry by the ETS.

Furthermore, we consider the change in the market share of the compliance firm $\Delta\hat{\lambda}$ under $h = 1$ and different ε, in order to illustrate the cost crowding-in mechanism. The change in the market share of the compliance firm $\Delta\hat{\lambda} = \hat{\lambda}^Y - \hat{\lambda}^N$, and $\hat{\lambda}^Y$ denotes the market share of the compliance firm after the launch of the ETS, i.e., $\hat{\lambda}^Y = \hat{q}_1^Y/(\hat{q}_1^Y + \hat{q}_2^Y)$. Figure 3 shows the effect of the parameter combinations on the change in the market share of the compliance firm at $h = 1$.

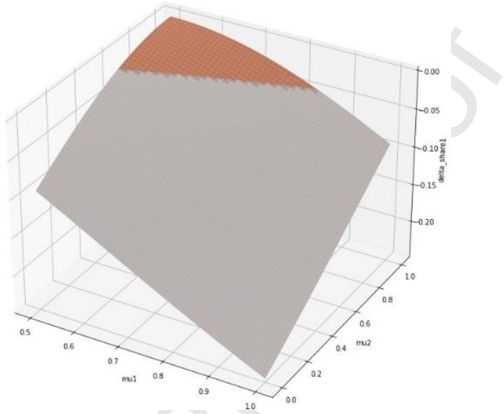
When $h = 1$ and $\varepsilon < 1$, $\Delta\hat{\lambda} < 0$ holds, which indicates that the market share of the compliance firm decreases after the launch of the ETS. This means that, under a low ε i.e. a low ETS coverage ratio, the additional costs of the compliance enterprises from the ETS lead to the disguised cost advantages of the uncovered enterprises in the same industry. Then the market share of the uncovered enterprises increases, while that of the compliance enterprises decreases. Therefore, the cost crowding-in mechanism is verified, in which the additional costs of the compliance enterprises crowd in the production and emissions of the uncovered enterprises in the same industry.

As the ε increases, the parameter combinations resulting in the increased industry-level emissions become less, and the decrease in the market share of the compliance firm becomes less. When $\varepsilon = 0.4$ and $\mu_1 = 0.5$, $\mu_2 \geq 0.4$ will lead to the phenomenon above, and the market share of the compliance firm will decrease by no more than 3.63%. When $\varepsilon = 0.6$ and $\mu_1 = 0.5$, $\mu_2 \geq 0.6$ will lead to the phenomenon above, and the market share of the compliance firm will decrease by no more than 1.71%. When $\varepsilon = 0.8$ and $\mu_1 = 0.5$, $\mu_2 \geq 0.8$ will lead to the phenomenon above, and the market share of the compliance firm will decrease by no more than 0.42%. These results show that, a high ETS coverage ratio can limit the cost crowding-in mechanism, and control the intra-industry carbon leakage. These help the industry-level emissions decrease under the carbon mitigation of the compliance enterprises.

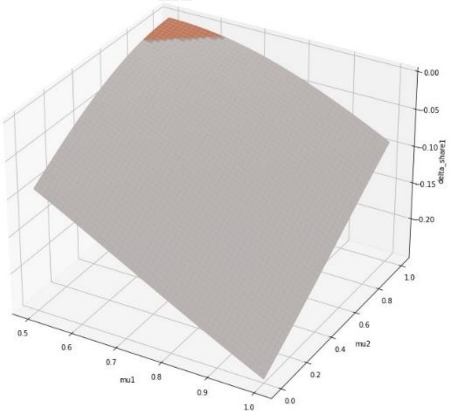
A series of results above show that, under a certain formation mechanism for the carbon price, the carbon mitigation of the compliance enterprises will incentive the uncovered enterprises to expand their productions and emissions due to the cost crowding-in mechanism. If the proportion of the regulated enterprises in the industry is low, the degree of increase in the emissions of the cost crowding-in mechanism is greater than the degree of carbon mitigation of the compliance enterprises, which will lead to an increase in the overall emissions of the industry in spite of the carbon mitigation of the compliance enterprises. Effective control of this phenomenon depends not only on an ETS that comprehensively monitors the emission intensities of enterprises in the industry, but also on dynamically expanding the scope of the regulated enterprises in the industry.



(a) $\hat{\lambda}^N = 44.4\%$ $(\varepsilon = 0.4)$



(b) $\hat{\lambda}^N = 54.5\%$ $(\varepsilon = 0.6)$



(c) $\hat{\lambda}^N = 61.5\%$ $(\varepsilon = 0.8)$

Figure 3 Results for $\Delta\hat{\lambda}$ under different combinations $(\varepsilon, \mu_1, \mu_2)$ when $h = 1$

Note: Orange areas indicate the combinations(μ_1, μ_2) leading to an increase in the overall emissions of the industry $\Delta\hat{e} > 0$.The X-axis indicates the value of μ_1, the Y-axis indicates thevalue of μ_2, and the Z-axis indicates the value of $\Delta\hat{\lambda}$.

These conclusions can be verified by the actual situation in Guangdong pilot ETS. In Guangdong, the ETS only adopts the carbon emissions as the benchmark for the inclusion of enterprises, and the coverage ratio is relatively low. These have led to an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises. The enterprise inclusion mechanism of the Guangdong pilot market is similar to that of the national ETS and the other regional pilot ETS, in which enterprises with high carbon emissions are included in the regulation. If the enterprises reduce their emissions below certain level, they will be dynamically screened out of the regulation. Under this mechanism, the number of enterprises regulated by Guangdong pilot ETS accounts for only 3.3% of the total number of enterprises in the corresponding industry, as shown in Figure 4. Therefore, the ETS internalizes the emission costs of the compliance enterprises and raises their production costs, but a large number of enterprises are not regulated, gaining certain cost advantages in disguise and increasing productions and emissions. This results in the fact that, the degree of increase in the emissions of the uncovered enterprises is greater than the degree of carbon mitigation of the compliance enterprises, leading to an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises. In consequence, the ETS fails to effectively constrain the emission level of the industry as a whole.

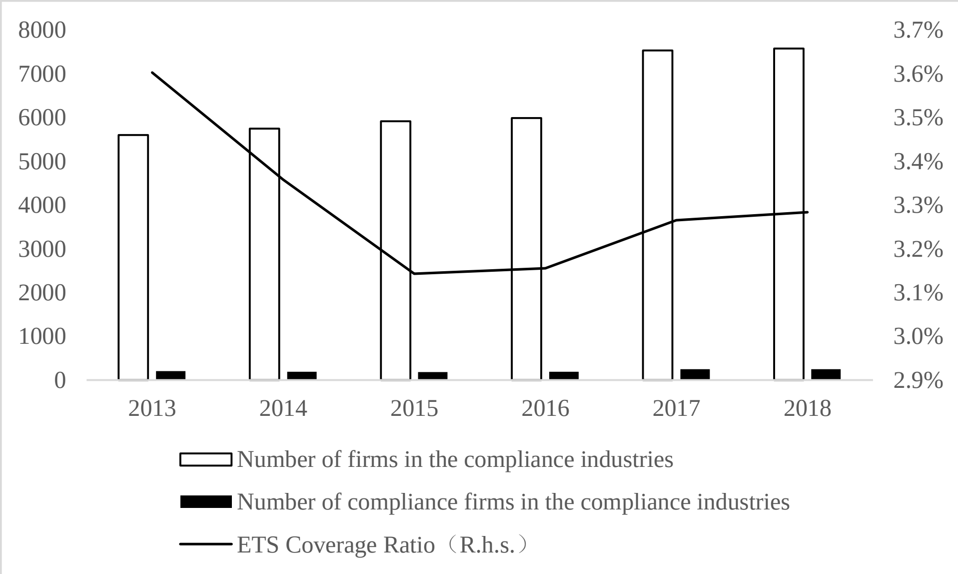
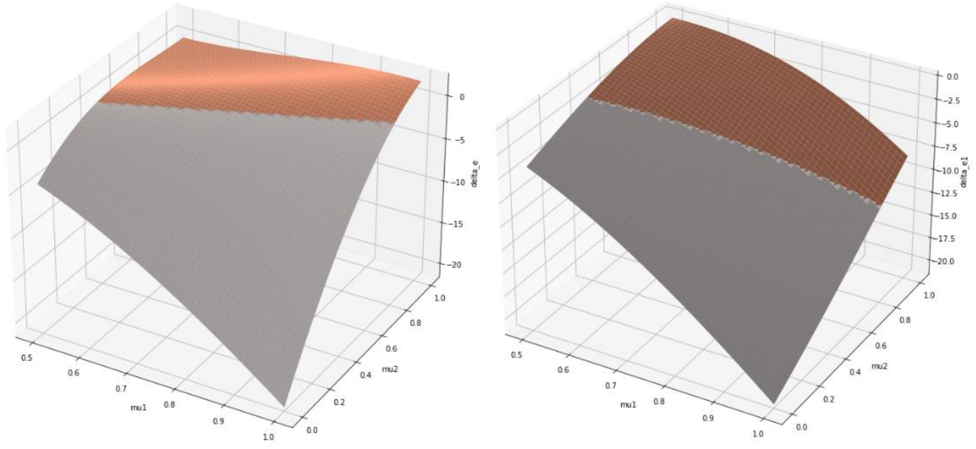


Figure 4 ETS coverage ratio of the compliance enterprises in Guangdong Pilot ETS

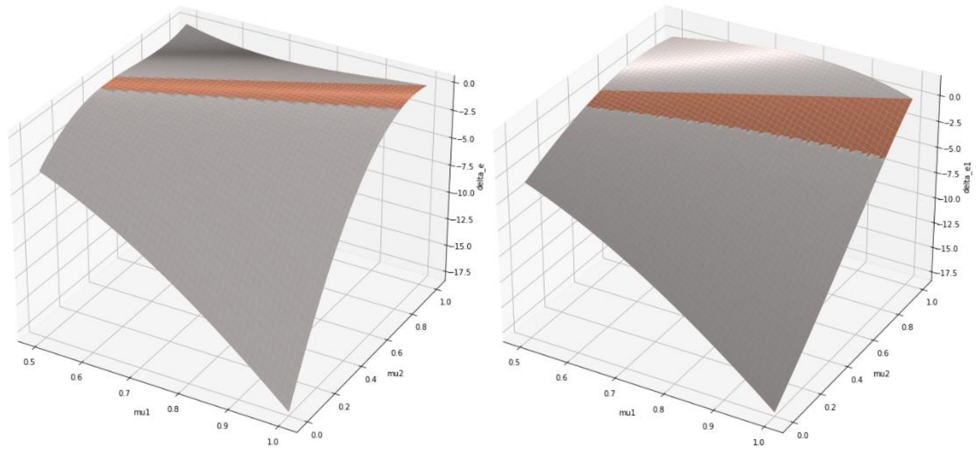
Note: ETS coverage ratio is the number of compliance firms divided by the number of all firms in the compliance industries.

4.2.3. ETS market competitiveness and cost crowding-in

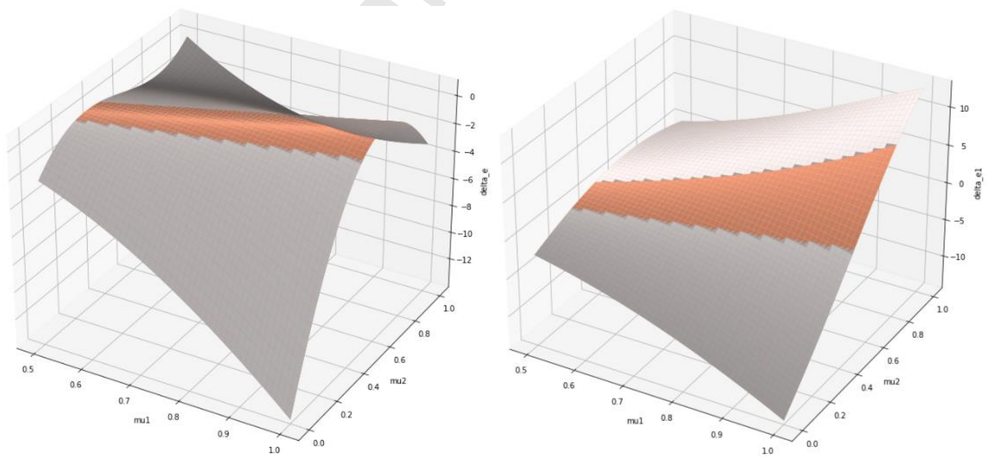
Under the condition $\varepsilon < 1$ ($\hat{\lambda}^N < 66.7\%$), we examine the effect of the parameter h on the emissions. Figure 5 shows results when $\varepsilon = 0.4$ ($\hat{\lambda}^N = 44.4\%$). The results show that, as the parameter h increases, there will be less combinations (μ_1, μ_2) leading to an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises. However, as the parameter h increases, there is a possibility of increasing emissions of the compliance firm.



(a) $h = 1$



(b) $h = 1.5$



(c) $h = 2$

Figure 5 Results for $\Delta\hat{e}$ (left) and $\Delta\hat{e}_1$ (right) under different combinations (h, μ_1, μ_2) when $\varepsilon = 0.4$

Note: Orange areas indicate the combinations(μ_1, μ_2) leading to an increase in the overall emissions of the industry$\Delta\hat{e} > 0$.The X-axis indicates the value of μ_1, the Y-axis indicates thevalue of μ_2, and the Z-axis indicates the value of $\Delta\hat{e}$(left) and $\Delta\hat{e}_1$ (right).

Take $h = 1.5$ and $\varepsilon = 0.4$ ($\hat{\lambda}^N = 44.4\%$) as an example. When $\mu_1 = 0.5$, only $0.4 \leq \mu_2 \leq 0.5$ will lead to an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises. However, in this situation, $\mu_2 > 0.5$ will lead to the increase in emissions of the compliance enterprises. When $\mu_1 = 0.7$ or $\mu_1 = 0.9$, it is necessary to satisfy $0.56 \leq \mu_2 \leq 0.7$ or $0.72 \leq \mu_2 \leq 0.9$, respectively, leading to an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises. However, $\mu_2 > 0.7$ or $\mu_2 > 0.9$, respectively, will lead to the increase in emissions of the compliance enterprises.

Compare with the situation when $h = 1$ and $\varepsilon = 0.4$. Firstly, under a certain emission intensity of the compliance firm, with the parameter h increases, the lowest emission intensity of the uncovered firm leading to the phenomenon above remains unchanged, but the highest one is limited. Then there are less parameter combinations (μ_1, μ_2) leading to the phenomenon above. Secondly, with the parameter h increases, once the emission intensity exceeds the highest level leading to the phenomenon above, the compliance firm increases the emissions despite the carbon mitigation of the industry as a whole. When the parameter h is large, the impact of emissions and the demand for emission allowances on the carbon price is weak, then the compliance firms compensate for the emission costs by expanding productions and capturing monopoly profits in the market, which increases its emissions and market share. The market share of the uncovered firm in the industry is squeezed, reducing its productions and emissions.

The results can be analyzed from two perspectives. From the perspective of compliance firms, a weaker ETS market competitiveness may lead to an increase in compliance firms' emissions. Under a larger parameter h, the decrease in carbon price is weak in response to the decrease in the allowances. In order to reduce abatement costs, i.e. carbon price, compliance enterprises choose to increase allowance allocation e_0, rather than decrease their emissions e_1^Y. Therefore, compliance firms increase their productions and emissions in order to increase allowance allocation $e_0 = (\mu_1 + \mu_2) q_1^Y / 3 = (e_1^Y + \mu_2 q_1^Y)/3$.

From the perspective of the whole industry, a weaker ETS market competitiveness may lead to a decrease in industry-level emissions. Since the compliance firms increase their productions and emissions, the uncovered firms in the same industries have to decrease their productions, as shown in Appendix E. Then the industry-level emissions decrease, though compliance firms' emissions increase.

4.2.4. ETS coverage ratio and market competitiveness

ETS market competitiveness may have different effect on firm-level and industry-level emissions. We further investigate the optimal competitiveness, which can most probably decrease firm-level and industry-level emissions simultaneously.

Based on parameter settings in Table 8, we further consider more values for parameter h. We set the value one by one in the $[0.2,3]$ interval with a step of 0.2, under a constant parameter $g = 1$. We examine the change in firm-level and industry-level emissions, i.e. $\Delta\hat{e}_1$ and $\Delta\hat{e}$, under different combinations $(h, \varepsilon, \mu_1, \mu_2)$. Then we calculate the probabilities and levels for decreased emissions, as shown in Table 9.

Firstly, consider a low ETS coverage ratio, e.g. $\varepsilon = 0.4$. A relatively high competitiveness ($h \leq 1$) can ensure a decreased emissions for compliance firms, but may increase industry-level emissions under some combinations (μ_1, μ_2). However, a medium competitiveness ($h = 1.2$) can maximize the probability for simultaneous decreases in firm-level and industry-level emissions, though the decreases are not the largest. Therefore, under a low ETS coverage ratio, which may be in the early stage of the ETS, the market competitiveness should be in a medium level.

Secondly, consider an increasing ETS coverage ratio. The optimal competitiveness increases, i.e., the parameter h, which most probably simultaneously decreases firm-level and industry-level emissions, becomes lower. Especially under a high ETS coverage ratio e.g. $\varepsilon = 1$, decrease in firm-level emissions regularly leads to decrease in industry-level emissions. In this situation, a high competitiveness can decrease most emissions and improve the carbon mitigation effect of the ETS.

Table 9 Change in emissions under different combinations $(h, \varepsilon, \mu_1, \mu_2)$

ε	Statistics	h									
		0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
0.4	$e_1^\uparrow$	None	None	None	None	None	0.08	0.38	1.06	2.21	3.69
	$e^\uparrow$	1.99	1.71	1.42	1.10	0.76	0.45	0.18	0.01	0.05	0.29
	$P(e^\downarrow \mid e_1^\downarrow)$	60.1%	60.1%	60.1%	60.1%	60.1%	60.4%	60.3%	60.3%	50.4%	38.3%
	$e^\downarrow \mid e_1^\downarrow$	-7.16	-6.77	-6.34	-5.88	-5.38	-4.80	-4.20	-3.53	-3.34	-3.22
	$e^\downarrow \mid e_1^\uparrow$	None	None	None	None	None	-0.09	-0.29	-0.53	-0.94	-1.47
0.6	$e_1^\uparrow$	None	None	None	None	None	0.08	0.38	1.06	2.21	3.69
	$e^\uparrow$	0.41	0.33	0.26	0.18	0.09	0.03	0.00	0.12	0.44	0.96
	$P(e^\downarrow \mid e_1^\downarrow)$	86.3%	86.3%	86.3%	86.3%	86.3%	86.6%	83.5%	65.5%	50.4%	38.3%
	$e^\downarrow \mid e_1^\downarrow$	-6.96	-6.53	-6.05	-5.54	-4.97	-4.33	-3.77	-3.83	-3.75	-3.49
	$e^\downarrow \mid e_1^\uparrow$	None	None	None	None	None	-0.03	-0.08	-0.18	-0.27	-0.38
0.8	$e_1^\uparrow$	None	None	None	None	None	0.08	0.38	1.06	2.21	3.69
	$e^\uparrow$	0.06	0.05	0.03	0.02	0.01	0.00	0.06	0.29	0.78	1.49
	$P(e^\downarrow \mid e_1^\downarrow)$	97.1%	97.1%	97.1%	97.1%	97.1%	95.5%	83.5%	65.5%	50.4%	38.3%
	$e^\downarrow \mid e_1^\downarrow$	-7.39	-6.89	-6.34	-5.75	-5.09	-4.45	-4.17	-4.12	-3.95	-3.62
	$e^\downarrow \mid e_1^\uparrow$	None	None	None	None	None	-0.01	-0.02	-0.04	-0.05	-0.06
1.0	$e_1^\uparrow$	None	None	None	None	None	0.08	0.38	1.06	2.21	3.69
	$e^\uparrow$	None	None	None	None	None	0.01	0.11	0.42	1.03	1.87
	$P(e^\downarrow \mid e_1^\downarrow)$	100%	100%	100%	100%	100%	95.5%	83.5%	65.5%	50.4%	38.3%
	$e^\downarrow \mid e_1^\downarrow$	-7.91	-7.35	-6.74	-6.08	-5.35	-4.76	-4.40	-4.29	-4.07	-3.70
	$e^\downarrow \mid e_1^\uparrow$	None	None	None	None	None	None	None	None	None	None

Note: $e_1^\uparrow$ is the average of increased emissions of compliance firms. $e^\uparrow$ is the average of increased emissions of industry as a whole. $P(e^\downarrow \mid e_1^\downarrow)$ is the probability for decrease in industry-level emissions condition on decrease in compliance firms' emissions. $e^\downarrow \mid e_1^\downarrow$ is the average of decreased industry-level emissions condition on decrease in compliance firms' emissions. $e^\downarrow \mid e_1^\uparrow$ is the average of decreased industry-level emissions condition on increase in compliance firms' emissions.

In summary, although market competitiveness may increase firm-level or industry-level emissions in some situations, it is optimal for ETS governors to develop a competitive market. In the early stage of the ETS when coverage ratio is low, it is optimal to maintain a weakly competitive market. With the development of the ETS and coverage ratio, a strongly competitive market is needed. It can not only avoid phenomenon of an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises, but also rapidly and efficiently decrease industry-level emissions.

Moreover, compared to market competitiveness, ETS coverage ratio plays a more important role in industry-level carbon mitigation. Under a low coverage ratio, a higher competitiveness may lead to a more severe risk for increased industry-level emissions. A competitive market under sufficient coverage is crucial for simultaneous carbon mitigation at firm and industry levels.

Compared to the other pilot ETS in China, Guangdong ETS market competitiveness is relatively high. There is an insignificant correlation between carbon price and allowance cap[16]. On the one hand, this is due to the timely and clear disclosures about allowance caps and allocation mechanisms. Compliance firms can reduce their abatement costs through decreasing emissions. On the other hand, this is attributed to active participations in ETS market transactions. This leads to high ability of carbon price to reflect the demand for emission allowances.

4.3. Typical facts

The theoretical analysis shows that, low ETS coverage ratio leads to an increase in the overall emissions of the industry. Case study on two typical industries further provides evidence for the cost crowding-in mechanism. In Guangdong pilot ETS, the impact of the cost crowding-in mechanism is particularly prominent in the cement as well as iron and steel industries. These two industries are the top two manufacturing industries in the carbon emissions in Guangdong[17], with relatively close market shares, industrial scales, the degrees of development of emission reduction technology. Also, they were simultaneously included in Guangdong pilot ETS in 2013. Therefore, they are similar in many other aspects, of which the carbon mitigation effect will be closely related to the ETS coverage mechanism.

Figure 6 shows the ETS coverage ratio and the carbon emissions of the two industries in Guangdong. The carbon intensities of both were relatively consistent, maintaining a certain level for a long time, and faced small decrease after the launch of the ETS. Since the emission reduction technologies in the two industries were in the early stage of research and development, the significant reductions of their carbon intensities were still weak, pending the wide application of new production processes and various new raw materials.

In terms of the carbon emission, there is a better carbon mitigation effect in the iron and steel industry, where more enterprises are included in the carbon market. The carbon emissions of the iron and steel industry maintained a downward trend after 2013, and faced a simultaneous increase in the productions and carbon emissions in 2017~2018 due to the rapidly increasing downstream demand[18]. In contrary, the carbon emissions of the cement industry showed an upward trend after 2013. Moreover, the number of cement enterprises regulated by the ETS gradually decreased while the number of newly operating cement enterprises continued to increase.

The results above suggest that, the low ETS coverage ratio in the cement industry is an important reason why the carbon emissions in the cement industry rose rather than fell after the launch of the ETS. The competitive advantage of cement enterprises regulated by the ETS reduced, attracting the uncovered cement manufacturers who do not need to pay additional emission costs as well as the new entrants to increase cement production, leading to an increase in the overall carbon emissions in the cement industry. On the other hand, in the iron and steel industry, the high ETS coverage ratio helped to significantly reduce the industry-level carbon emissions after the launch of the ETS.

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16 The correlation between carbon price and allowance cap is -17% with a p-value of 0.74. The carbon price and allowance cap amount are in in natural logarithm.

17 In 2019, the cement industry (non-metallic mining industry) emitted about 83 million tons of CO_2, and the iron and steel industry (ferrous metal smelting and rolling processing industry) emitted about 33.15 million tons of CO_2, which are the top two carbon emitters among the manufacturing industries in Guangdong.

18 In 2017 in Guangdong, the output of pig iron, crude steel and steel increased year-on-year by 21.21%, 26.61% and 2.44%, respectively. Among them, the production of pig iron and crude steel will emit the highest carbon emissions in the steel production process.

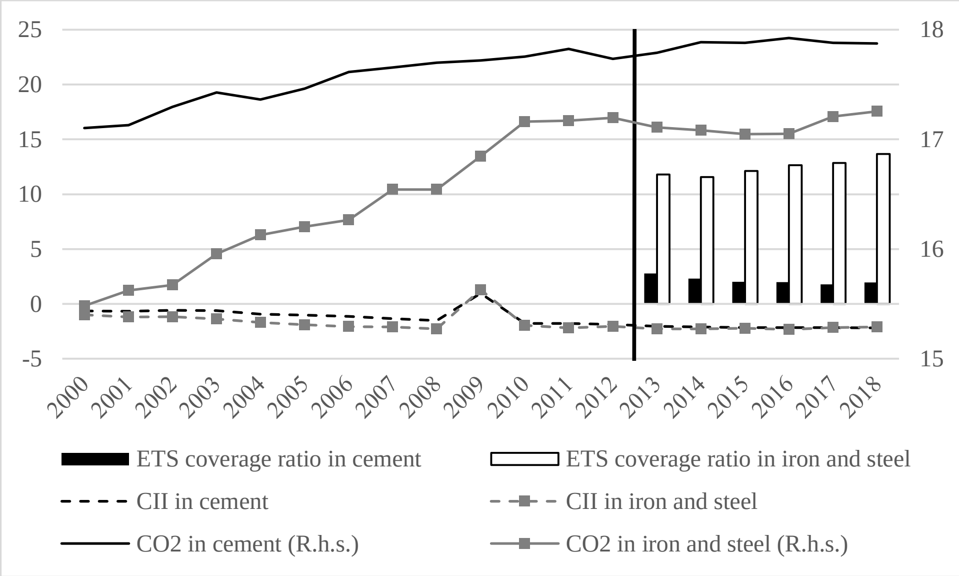

Figure 6 Comparison of the emissions and the ETS coverage ratio between the cement and iron & steel industries in Guangdong

Note: The black vertical line indicates the year when the cement and iron and steel industries were included in the Guangdong pilot ETS, i.e., year 2013. The ETS coverage ratio is the number of compliance firms divided by the number of all firms in the compliance industries. The CO2 is the carbon emissions of the industry in natural logarithm. The CII is the carbon intensities of the industry in natural logarithm.

5. Conclusions and Policy Implications

From the perspective of intra-industry carbon leakage, we propose for the first time that China's ETS leads to the phenomenon of an increase in the overall emissions of the industry in spite of the carbon mitigation of the compliance enterprises. We provide the empirical evidence, and theoretically explain the internal mechanism and underlying reason for this phenomenon.

The results show that: (1) At the industry level, the regional pilot ETS has not yet effectively reduced the overall carbon emissions. The ETS leads to intra-industry carbon leakage, i.e., an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises. (2) Theoretical analysis shows that, the cost crowding-in mechanism is the main reason for this phenomenon. After the launch of the ETS, the production cost of the compliance enterprises will increase under the internalization of emission costs. However, the uncovered enterprises in the same industry will gain the competitive advantage in expanding their productions and emissions. Through the cost crowding-in mechanism, the carbon emissions of the compliance enterprises leak to the uncovered enterprises in the industry, leading to the intra-industry carbon leakage. (3) There are two ways to effectively weaken the impact of the cost crowding-in mechanism, manage the intra-industry carbon leakage, and promote the ETS to reduce the overall emissions of the industry. One of them is increasing the ETS coverage ratio. The other is incentivizing the compliance enterprises to actively participate in the market transaction, which enhances the ability of the carbon price to reflect the demand for carbon allowances of enterprises.

The findings of this study have important policy implications for the development and improvement of China's ETS as follows.

Firstly, the ETS coverage ratio needs to be enhanced. It is helpful to accelerate the expansion of the regulatory coverage of the ETS for the enterprises in the existing compliance industries, to scientifically manage the intra-industry carbon leakage, and to ensure that the carbon mitigation effect of the ETS spreads from the key enterprises to the whole specific industry. Currently, the intra-industry carbon leakage has led to the phenomenon of an increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises, indicating the failure in the spread of the carbon mitigation effect.

Secondly, it is necessary to guide the compliance enterprises to participate in ETS market transactions in order to enhance the ability of the carbon price to reflect the demand for emission allowances of the enterprises. On the one hand, the effective industry-level carbon mitigation of the ETS depends on the cooperation with "visible hand" of the government and the "invisible hand" of the market. The ETS is a government-led market-based tool for reducing emissions. The government plans the top-level design and the related details for the market trading, and the carbon mitigation effect relies on the market-based trading and operation of the compliance enterprises. Cultivating the market-based trading capacity of the compliance enterprises, and guiding the market participants, especially the compliance enterprises, to actively participate in market transactions can be the important basis for the long-run carbon mitigation by the ETS. On the other hand, it is expected to standardize the investor management policies of the ETS market, to strengthen the supervision of the market tradings of the non-compliance enterprises and institutions, and to avoid the disturbance of the regulatory role of the carbon price. Some measures can be taken, such as strengthening the expectation management of the carbon price, developing the derivatives market for emission allowance, and providing risk management tools for the compliance enterprises.

Thirdly, the criteria of the ETS coverage should be optimized, in order to establish a dynamic covering, monitoring and supervision mechanism based on the emission intensities. Currently, the carbon emissions are the only standard for the coverage of the enterprises by the ETS. In this situation, some enterprises with higher emission intensities and lower productions will not be regulated by the ETS. If these uncovered enterprises increase their productions and emissions under the influence of the cost crowding-in mechanism even though the compliance enterprises reduce emissions, there may be the phenomenon of an increase in the overall emissions of the industry. Some measures are proposed, such as comprehensively monitoring the emission intensities of all the enterprises in the compliance industries, implementing the ETS coverage mechanism based on emission intensities, and dynamically adjusting the scope of regulation on the enterprises on the basis of emission intensities.

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Appendix

Appendix A. Facts on the increase in the overall emissions of the industry despite the carbon mitigation of the compliance enterprises in Guangdong

For a long time, it has been difficult to obtain detailed data on the operation and the emissions of the compliance enterprises in the regional pilot ETS. In comparison, the monitoring and disclosure of data on the overall emissions of the industry is easier. In 2018, the "Bulletin on the Ecological and Environmental Conditions of Guangdong Province in 2018" released for the first time the statistical data related to the carbon mitigation of the compliance enterprises, but it only qualitatively stated that “the carbon intensity of enterprises has continued to decline”. In 2021, the “Bulletin on the Ecological and Environmental Conditions of Guangdong Province in 2021” released the statistics for the first time, which indicated that the carbon emissions of the compliance enterprises regulated by Guangdong pilot ETS in 2021 had been reduced by 16% compared with that in 2013. Combined with many related literatures, the carbon mitigation of the compliance enterprises is fully supported.

However, there is an increase rather than a decrease in the overall emissions of the compliance industries during the same period. Compared with 2013, the overall carbon emissions of the compliance industries increased by about 12.3% in 2018. In 2021, though the statistical data of carbon emissions at the industry level are not yet available, the statistical data of energy consumption at the industry level show that, the overall energy consumptions of the compliance industries increased by about 14.7% in 2021 compared with 2013. These suggest that there seem to be an increase in the overall emissions of the industry.

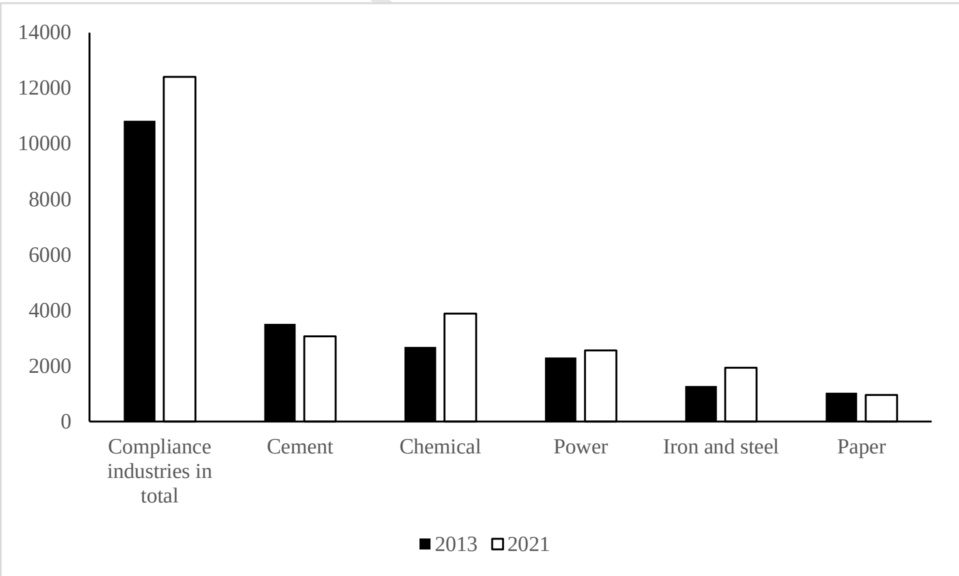


Figure A1: Changes in total energy consumptions of the compliance industries in Guangdong (in 10,000 tons of standard coal)

Source: Guangdong Statistical Yearbook.

Appendix B. Summary statistics of variables for Hubei sample

Statistics of most variables for Hubei sample are similar to that for Guangdong sample, including emissions, industrial output and industry risk. However, in Hubei sample, there are relatively less enterprises, which means that industries in Hubei tend to be composed of a few large enterprises. Moreover, there are larger deviations in industrial output and industry risk in Hubei sample, which shows a relatively unbalanced development compared to Guangdong.

Table B1 Summary statistics of variables for Hubei sample

Variables	Mean	Standard deviation	Minimum	Maximum
Panel A. Hubei sample				
$CO2$	13.3451	2.0250	9.2103	18.5768
CII	-3.8186	1.9940	-8.0582	1.1712
Number of enterprises	5.1271	1.5823	0	7.4872
Gross industrial output value	17.1586	1.5659	11.4721	20.0056
Current ratio	1.1446	0.5165	0	4.0793
Panel B. Guangdong sample				
$CO2$	13.6859	1.7806	10.4448	19.3874
CII	-4.5126	1.7400	-7.4256	0.4532
Number of enterprises	6.2729	1.5378	0.6931	8.5340
Gross industrial output value	18.1888	1.4639	13.5558	21.4869
Current ratio	1.1910	0.3455	0.1944	4.1717

Note: Sample range from 2000 to 2018. Sample size for Hubei sample is 541. Sample size for Guangdong sample is 643. The zeros in Number of enterprises are in the industry Petroleum and Natural Gas Mining, where there are only one firm in some years. The zeros in Current ratio are the observations where current assets equal to zero.

Appendix C. The effect of Guangdong pilot ETS on industry-level emissions under different control variables

The control variables for Guangdong sample are different from that for Hubei sample. In order to test the robustness under different control variables, we test the effect of Guangdong pilot ETS on industryl-level emissions under the control variables same as that for Hubei sample.

The results are shown in Table C1. Under different control variables, the launch of Guangdong pilot ETS still increases industry-level carbon emissions and carbon intensities. These results illustrate the robustness of our findings.

Table C1 Results under different control variables

	(1)	(2)
	$CO2$	CII
$Treat \times Post$	0.2577***	0.3060***
	(2.88)	(3.19)
Number of enterprises	-0.0438	-0.0644
	(-0.74)	(-1.02)
Gross industrial output value	0.0521	-0.9066***
	(1.11)	(-16.65)
Current ratio	-0.5783***	-0.5793***
	(-6.24)	(-6.30)
Constant	12.1863***	11.6201***
	(14.75)	(12.64)

Industry fixed effect	Yes	Yes
Year fixed effects	Yes	Yes
N	643	643
adj. R^2	0.9612	0.9555

Note: t-values based on robust standard errors are in parentheses. *, ** and *** denote 10%, 5% and 1% significance levels, respectively. Guangdong sample is used. Regression model is $emission_{j,t} = \beta_1 + \beta_2(Treat_j \times Post_{j,t}) + ControlHB + FE + e_{j,t}$.

Appendix D. The allowance cap in Guangdong pilot ETS

We consider two measures for allowance cap, $CAP1$ and $CAP2$. $CAP1$ is the allowance cap amount divided by total carbon emissions in Guangdong. $CAP2$ is the allowance cap amount divided by total carbon emissions of compliance industries in Guangdong. The data are organized according to the announcements of the Guangdong Provincial Department of Ecology and Environment.

The allowance cap in Guangdong pilot ETS is low and shows a downward trend. This shows that, Guangdong pilot ETS keeps a strong and gradually strengthened supervision.

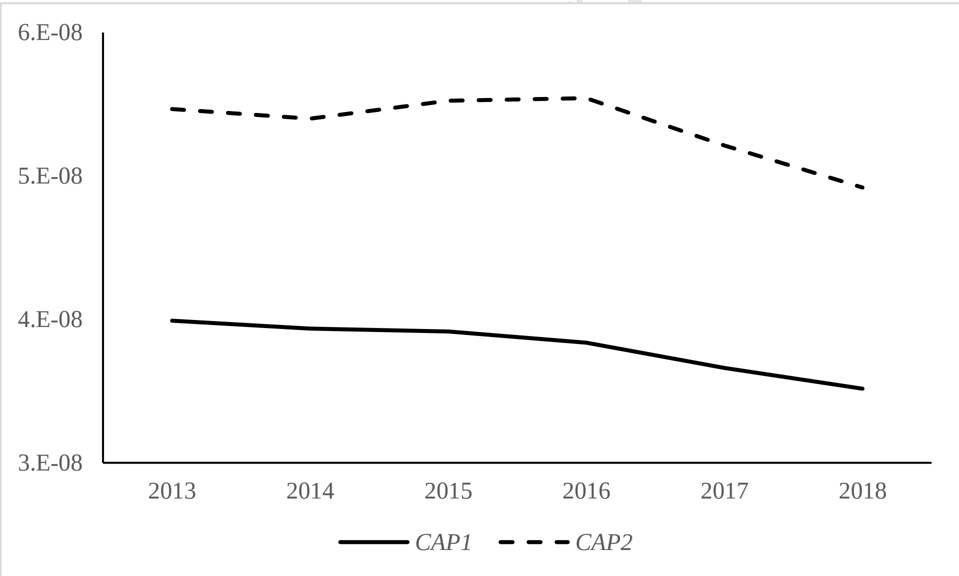


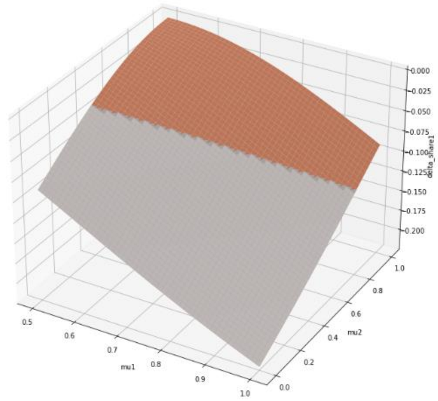
Figure D1: The allowance cap in Guangdong pilot ETS

Source: Organized according to the aannouncements of the Guangdong Provincial Department of Ecology and Environment.

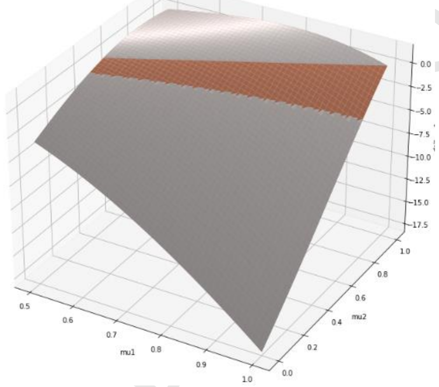
Appendix E. ETS market competitiveness and market shares of compliance firms

We consider the change in the market share of the compliance firm $\Delta\hat{\lambda}$ under $\varepsilon = 0.4$ and different h, in order to illustrate the cost crowding-in mechanism. Results are shown in Figure E1.

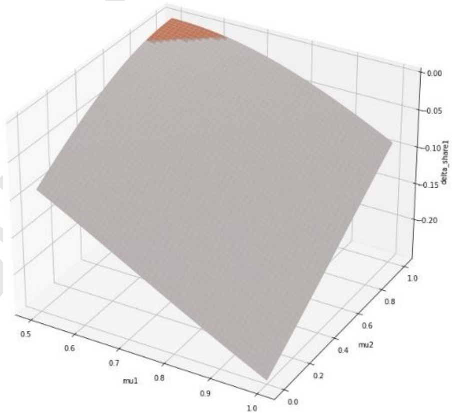
Under the situation $h > 1$ where market competitiveness is relatively weak, an increase in compliance firms' emissions is accompanied by an increase in their market shares. The compliance enterprises choose to monopolize the market by expanding their scale in order to obtain monopoly profits to make up for the additional costs. The uncovered enterprises face a compressed market share, and accordingly reduce their productions and emissions.



(a) $h = 1$



(b) $h = 1.5$



(c) $h = 2$

Figure E1 Results for $\Delta\hat{\lambda}$ under different combinations (h, μ_1, μ_2) when $\varepsilon = 0.4$

Note: Orange areas indicate the combinations(μ_1, μ_2) leading to an increase in the overall emissions of the industry $\Delta\hat{e} > 0$.The X-axis indicates the value of μ_1, the Y-axis indicates thevalue of μ_2, and the Z-axis indicates the value of $\Delta\hat{\lambda}$.

Highlights for

Carbon Mitigation Effect of Emission Trading Product: Perspective from Intra-Industry Carbon Leakage

1. This study examines the effect of China’s ETS on industry-level emissions.

2. Counterintuitively, ETS leads to increased emissions in compliance industries despite compliance firms’ mitigations.

3. Intra-industry carbon leakage results in this increased industry-level emissions, notably through cost crowding-in mechanism.

4. ETS coverage ratio and market competitiveness can help regulate intra-industry carbon leakage.

5. It adds to the literature about assessment of ETS policy from a new perspective of intra-industry carbon leakage.