Effects and Mechanism of Carbon Emission Trading Scheme on Carbon Emission Reduction in China

By XIAOQUAN GAO, CUIPING LIAO AND JIAXIN HE*

Evaluation of the carbon trading strategy is of great importance to improve the policy design to reduce carbon emissions and mitigate climate change. To significantly eliminate estimation bias, we employed a Difference in Difference in Difference model (DDD) to evaluate the emission reduction effect of carbon trading policy and conducted heterogeneity analysis and impact channel discussion, on the back of three-dimensional data from 15 industrial sectors in China's 30 provinces from 1999 to 2019. The results show that the emission trading scheme (ETS) has a significant across-the-board impact on emission reduction, yet regional and industry heterogeneity is unmistakably visible. The channel analysis indicates that the effects are mostly attained through lowering overall energy consumption and increasing energy efficiency. Nevertheless, there is no change in the energy structure.

Xiaoquan Gao: Master, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, No.2 Nengyuan Road, Tianhe District, Guangzhou, 510000 (e-mail: gaoxq@ms.giec.ac.cn).

Cuiping Liao: Dr. Professor, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, No.2 Nengyuan Road, Tianhe District, Guangzhou, 510000 (e-mail: liaocp@ms.giec.ac.cn).

* Jiaxin He: Doctor, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, No.2 Nengyuan Road, Tianhe District, Guangzhou, 510000 (e-mail: hejx@ms.giec.ac.cn).

I. Introduction

Taking current environmental degradation into account, we can't keep a blind eye to the reality of the greenhouse effect, after all, it exerts a massive impact on the economic and social development. To address this problem, several governments have implemented a deluge of policies to reduce carbon emissions, including administrative regulations and laws (the EU Climate Act), market economy policies (carbon tariffs), and social engagement policies (promoting energy conservation). The Emission Trading Scheme (ETS), a market-based effort turns out to be a crucial tool in reducing carbon emissions worldwide. It is conducive to the effectiveness of emission reduction, cost-effectiveness, political acceptability, incentives for low-carbon energy and technology, and coordination with other global integration systems (Fu et al. 2022; Long et al. 2022; Hua, Cheng, and Wang 2011; Godal, Ermoliev, and Klaassen, n.d.). On top of the *Kyoto Protocol*, the global carbon market with the EU emission trading scheme (EU ETS) as its representative claims currently the world's oldest and largest carbon market (Guo et al. 2020; L. Liu et al. 2015). At present, 25 carbon markets are in operation throughout the world, such as the New Zealand emissions trading system (NZ ETS) in Asia & Pacific(Rontard and Reyes Hernández 2022) and the Regional Greenhouse Gas Initiative (RGGI) in Northern America (M.-K. Kim and Kim 2016).

China, the largest carbon emitter, has also been committed to addressing climate change in the long run and has implemented a suite of measures to reduce greenhouse gas (GHG) emission, such as the approval of the Clean Development Mechanism (CDM) and introduction of the concept of carbon trading in 2004. The year 2013 saw China officially launch the ETS, covering seven regions (Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Shenzhen, and Hubei). The establishment of Fujian's carbon market in 2016 makes the province into China's eighth pilot for carbon emission pricing. For each region, the industries covered by China ETS are different. Fig 1 depicts the scope of the ETS policy in China.

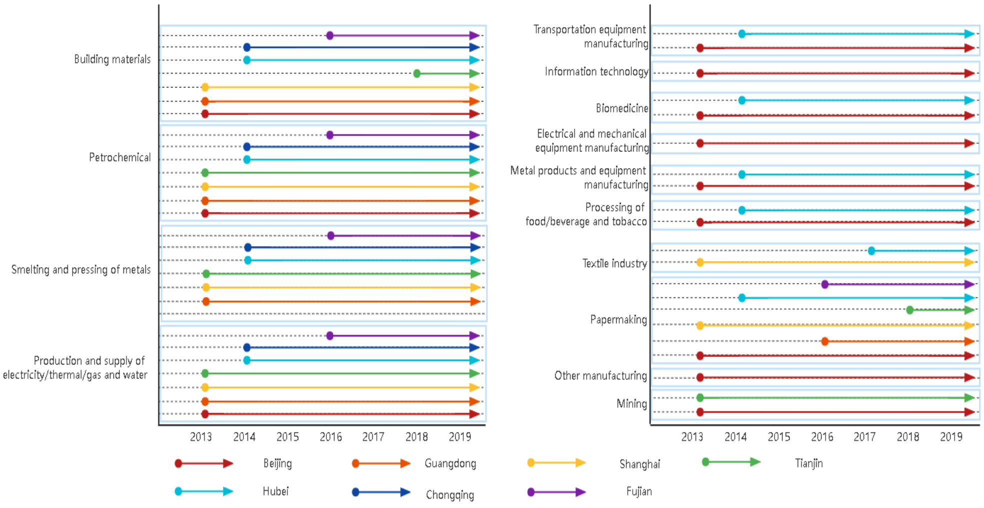


FIGURE 1. THE ETS PILOTS IN CHINA

In terms of ETS policy, a considerable amount of literature published makes two major issues the centerpiece - the design of the ETS policy and the evaluation of its economic and environmental effects. The previous study of the design of the ETS mainly put emphasis on allowance allocation(Goulder, Hafstead, and Dworsky 2010; Burtraw et al. 2001; Neuhoff, Martinez, and Sato 2006; Löfgren et al. 2018), cap setting(Stavins 2008a; 2008b), carbon prices(Ackerman and Stanton 2012; Arlinghaus 2015; Kirat and Ahamada 2011), and enforcement of compliance(Hovi and Holtsmark 2006). Especially, emission allowance prices vary significantly with the sector specific price elasticity of allowance demand, and further produce a rippling effect on the holistic emission reduction effect of society(Link et al. 2012).

Carbon markets can help decrease emissions despite low prices(Haites 2018; Bayer and Aklin 2020). Also, other researchers argued that in order to maintain the effectiveness of the carbon market, the allowance should be distributed at a higher price(Löfgren et al. 2018). The second most studied field is the evaluation of the

ETS policy. Several studies have shown that the ETS has effectively reduced emissions both at the enterprise and industry levels(Kirat and Ahamada 2011; Link et al. 2012; Haites 2018; Bayer and Aklin 2020; Klemetsen, Rosendahl, and Jakobsen 2016; Clarkson et al. 2015; Dechezleprêtre, Nachtigall, and Venmans 2018; Heiaas 2021). Save for environmental impacts, it has been proved that ETS has the potential to change the framework for doing business in the power sector and other energy-intensive industries(Martin, Muûls, and Wagner 2016), to exhort the purchase and use of industrial efficiency equipment(Hamamoto 2021), and to harm international trade(Dijkstra, Manderson, and Lee 2011; H. S. Kim and Koo 2011) and to affect firm competitiveness(Chan, Li, and Zhang 2013). Branger et al. pointed out the negative impacts of EU ETS, such as emission abatement being small, innovation being insufficient, competitiveness losses, distributional effects having indeed been unfair, and fraudulent(Branger, Lecuyer, and Quirion 2015). As a result, a few studies have centered on the topic of ETS reform, including the implementation of price limits and the development of complementary policies(Taschini, Kollenberg, and Duffy 2014; Rickels et al. 2021).

The previous studies about the ETS in China mainly focus on environmental and economic impacts. The environmental impacts of ETS are reflected in carbon emissions and carbon intensity. A number of empirical studies have revealed that the ETS significantly reduces carbon emissions at the provincial, prefecture, or industrial level respectively(S. Chen, Shi, and Wang 2020; Hu et al. 2020; Xuan, Ma, and Shang 2020; H. Zhang, Duan, and Deng 2019; W. Zhang et al. 2020). The ETS reduces carbon intensity by increasing the share of the output value of the tertiary industry in GDP and reducing energy consumption(Zhou et al. 2019; Tang et al. 2021). Economic effects are often explored in combination with environmental effects to test whether the ETS policy supports the Potter hypothesis(Z. Chen, Zhang, and Chen 2021). The main findings are that ETS has not led to the Potter hypothesis in the short term, but in the long term, ETS can produce sustainable economic dividends and environmental dividends(Tan and Lin 2022; W. Zhang et al. 2020; Dong et al. 2019). In addition, some research revealed that the ETS can expand employment, improve low-carbon innovation, boost low-carbon technological advances, sharpen the international competitiveness of the industry, and reduce the land supply of energy-intensive industries, but it fails to bolster Chinese enterprises to increase their R&D investment(Yang, Jiang, and Pan 2020; M. Liu et al. 2021; Zhu et al. 2019; Qi et al. 2021; Huang and Du 2020).

Given that China gives off the largest carbon emissions, it is of great importance to systematically evaluate emission reductions of China ETS. This study tries to distinguish from the previous literature the following aspects: 1). A far cry from most studies with a focus on one representative region or enterprise-level data for some big enterprises, we estimate the total emission reductions of the ETS policy in China using a three-dimensional panel (province, industry, year). In addition, taking advantage of the data structure, heterogeneity effects for different regions, as well as different industries, could be easily evaluated; 2). The Difference in difference in differences (DDD) method was employed to greatly eliminate estimation bias due to omitted variables, such as time-varying and time-invariant city characteristics (incl. local public policy and business cycle), time-varying and time-invariant industry characteristics (incl. technology changes in industries and industrial policies); 3). Based on the empirical model, we analyze the channel of the ETS policy from perspectives of energy structure, energy consumption, and energy efficiency.

Results

A. *Total emission reductions of ETS.*

Table 1 presents the results of total emission reductions of China ETS. In columns 1 to 4, different model specifications are used to estimate. The estimation coefficients of the ETS variable of the model in columns 1 to 3 are quite different, indicating that there exists a bias caused by omitted variables in the estimation. In the fourth column, the most rigorous model specification was applied to control for the three sets of interactive fixed effects simultaneously. It gives us, as a result, the most truthful results in emission reductions. The results in column 4 clearly illustrate that the coefficient of ETS is negative at a 1 percent significance level, suggesting that the ETS policy has effectively reduced carbon emissions. From the economic point of view, the implementation of the ETS can annually reduce 8.139 million tons of CO_2 for each province-industry pair, accounting for 36.88 percent of the average CO_2 emissions in each pair in 2019 (22.04 million tons of CO_2). Similarly, columns 5-8 produce the results of the impacts of the ETS policy on carbon intensity. In column 8, the estimation coefficient is -1.827, significant at a 1 percent level, meaning that the ETS averagely decreases the carbon intensity of each province-industry pair by about 182.7 tCO_2/CNY annually.

TABLE 1— MODELS TO ESTIMATE THE IMPACT OF ETS ON CARBON EMISSION

	Carbon Emission ($MtCO_2$)				Carbon Intensity ($MtCO_2$/10,000CNY)			
	(1)	(2)	(3)	(4)	(1)	(2)	(3	(4)
ETS	-0.375 (1.030)	-12.21^{***} (2.770)	1.253 (2.735)	-8.139^{***} (1.377)	-2.879^{***} (0.332)	-2.415^{***} (0.522)	-4.172^{***} (0.619)	-1.827^{***} (0.385)
_cons	14.00^{***} (0.194)	14.37^{***} (0.315)	13.95^{***} (0.334)	14.25^{***} (0.150)	4.823^{***} (0.0376)	4.806^{***} (0.0811)	4.869^{***} (0.0804)	4.785^{***} (0.0367)
Fixed effects								
Year FE	Yes				Yes			
Province FE		Yes				Yes		
Industry FE			Yes				Yes	
Province×Industry FE	Yes			Yes	Yes			Yes
Year×Industry FE		Yes		Yes		Yes		Yes
Province×Year FE			Yes	Yes			Yes	Yes
Number of observations	9289	9289	9289	9289	8158	8158	8158	8158
R^2	0.8371	0.6198	0.5547	0.9211	0.9233	0.6666	0.6637	0.9406

Notes: Specifications, coefficient estimates, and their statistical significances are shown for individual models. Standard errors are reported in parentheses under the coefficient estimates. Statistical significance level: * $p < 0.05$, **$p < 0.01$ and *** $p < 0.001$. R^2, indicates the proportion of the variance for dependent variable explained by the independent variables of the model.

B. Heterogeneity effects by different regions.

Bearing in mind significant differences in economic development level, topography, and climate among different regions, we analyzed the regional heterogeneous effects of the ETS policy. Fig.2 describes the estimation results of the heterogeneity analysis. The ETS policy significantly reduces carbon emissions in Tianjin, Shanghai, Fujian, Chongqing, and Hubei. The carbon intensity of Chongqing and Hubei has been remarkably lowered under the policy interventions. Based on the estimation coefficients, the ETS policy has the greatest effect on emission reductions in Chongqing, the second is Hubei. The interesting finding is that the ETS has decreased total emissions in Shanghai while increasing its carbon intensity. The implementation of the ETS policy in some regions, such as Beijing and Guangdong, is less successful.

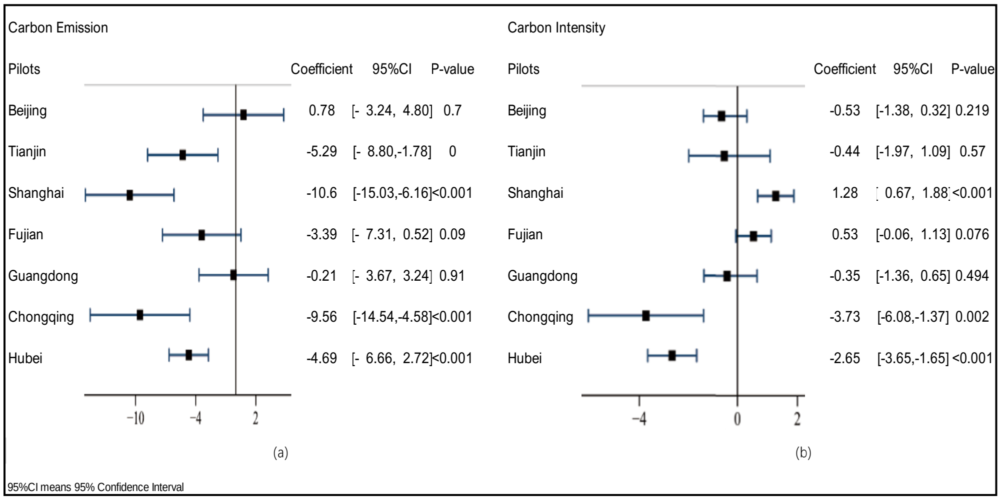


Figure 2. Regional Heterogeneity in effect of ETS Policy on Carbon Emission(a) and Carbon Intensity(b)

Notes: Fig.2 reports coefficients from equation (1) (Equation 1 will be mentioned in the Methods part.) The dependent variable is the implementation of ETS Policy. The displayed coefficients and their corresponding 95-percent level confidence intervals are for indicators of number of Carbon Emission(a) and Carbon Intensity(b).

C. Heterogeneity effects by different industries.

Fig.3 indicates the results of industry heterogeneity effects under the ETS policy intervention. According to the different features of different industries, all industries fall into five categories in the analysis.

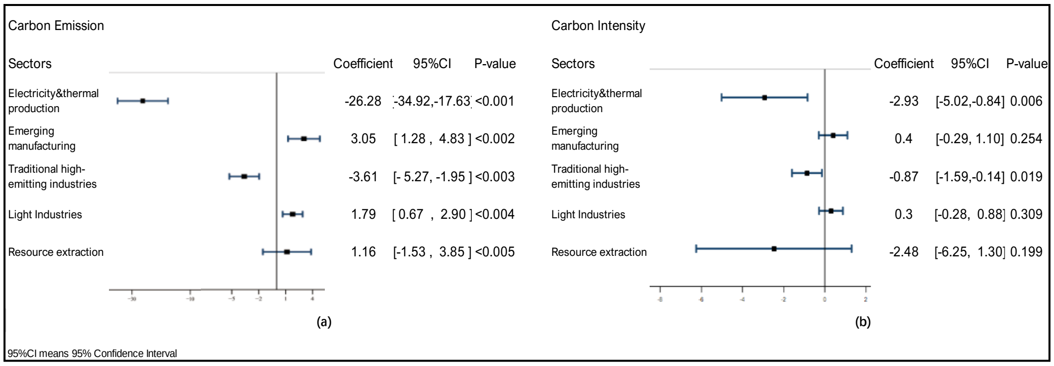


Figure 3. Industry Heterogeneity in effect of ETS Policy on Carbon Emission(a) and Carbon Intensity(b)

Notes: Figure 3 reports coefficients from equation (1) (Equation 1 will be mentioned in the Methods part.) The dependent variable is the implementation of ETS Policy. The displayed coefficients and their corresponding 95-percent level confidence intervals are for indicators of number of Carbon Emission(a) and Carbon Intensity(b).

Industry classification is described as follows: Electricity & thermal production—the production and supply of electricity, thermal energy, diesel fuel, and water； Traditional high-carbon industries—building materials, petrochemicals, and the smelting and pressing of metals； General conventional manufacturing sectors—food, beverage, and tobacco processing, textile, papermaking, and other manufacturing； Emerging manufacturing sectors—transportation equipment manufacturing, information technology, biomedicine, electrical and mechanical equipment manufacturing, and metal products and equipment manufacturing; Resource extraction—mining.

In electricity & thermal production and traditional high-carbon industries, the estimation coefficients for both carbon emissions and carbon intensity are significantly negative, marking that the implementation of the ETS policy has significantly reduced both the total carbon emissions and the carbon intensity. Among them, the electricity & thermal production industry has the largest effects of emission reductions led by the ETS policy. However, for the general conventional manufacturing industry and emerging manufacturing industry, the estimated coefficient of the ETS policy is positive, demonstrating that the ETS has increased the total emissions of these two categories. All these findings show that the ETS policy may transform the industrial structure of a region from high-energy-consuming manufacturing to less-energy-consuming.

The total emission reduction contributed by the ETS policy in China is shown in Fig. 4, which was computed by using the estimated results of the analysis. The emission reduction effects of electricity &thermal production and traditional high-carbon industries are obviously more significant than the negative impact of other industries. With the increase in pilot areas and the expansion of industry scope, the net emission reduction shows an increasing trajectory year by year.

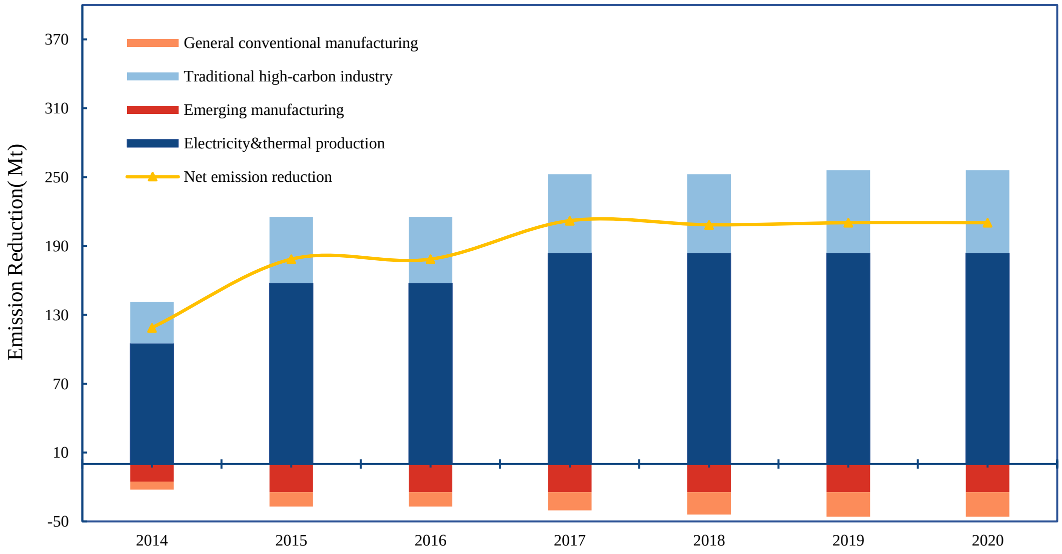


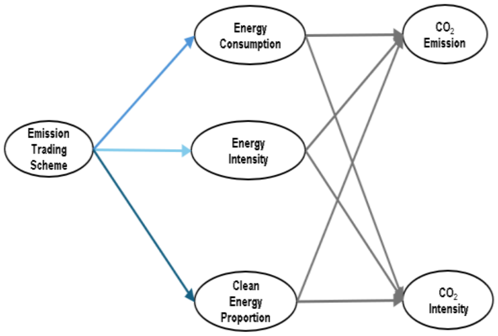
FIGURE 4. CARBON EMISSION REDUCTION FROM THE IMPLEMENTATION OF ETS POLICY.

Notes: The annual net emission reduction is calculated using the accumulated emission reductions made by each industry over time.

D. The impact mechanism by which ETS policy affects carbon emissions.

In China emission reductions are often in combination with energy control, such as reducing total energy consumption, improving energy efficiency, and upgrading energy structure. To explore how ETS policy reduces total carbon emissions, these three channels were tested by empirical analysis.

The estimated results of the impact of ETS on energy control are shown in Fig.5. It reveals that the implementation of ETS annually reduces overall energy consumption by 0.842 million tons of standard coal and lowers energy intensity by 74.2g/CNY for each province-industry pair. Reducing total energy consumption and energy intensity, therefore, are essential channels for the ETS policy. The most striking finding is that the ETS has decreased the portion of clean energy. In other words, the third channel generates the opposite effect. Next, we will further analyze the impact of the ETS policy on different kinds of energies.



mediation variables	coefficient	95% confidence interval	P value
Energy Consumption	-0.842	[-1.474,-0.210]	0.009
Energy Intensity	-0.742	[-1.372,-0.113]	0.021
Clean Energy Proportion	-0.05	[-0.072,-0.027]	0.000

FIGURE 5. THE RELATIONSHIP BETWEEN ETS AND ENERGY CONTROL ON CARBON REDUCTION

The impact of the ETS policy on different energies is shown in Table 2. The results clearly show that the ETS policy has significantly decreased the total consumption of electricity and coal, whereas no influence on oil and gas. However, when it comes to the consumption share of different energies, the estimation coefficients for electricity and coal are opposite. Specifically, the ETS policy has reduced the share of electricity and increased the share of coal. It further suggests that the ETS incentivizes industry to drastically cut electricity use to reduce emissions.

TABLE 2— MECHANISM ANALYSIS - ENERGY CONSUMPTION BY VARIETY

	Total consumption of different energies(Mt)				Proportion of consumption of different energies			
	electricity	oil	coal	gas	electricity	oil	coal	gas
ETS	-0.324***	0.144	-0.527**	-0.110	-0.0594***	0.00761	0.0315**	0.00975
	(0.0637)	(0.0822)	(0.186)	(0.0959)	(0.0110)	(0.00816)	(0.0107)	(0.00876)
_cons	0.751***	0.327***	1.977***	0.449***	0.335***	0.115***	0.366***	0.0925***
	(0.00590)	(0.00545)	(0.0203)	(0.00985)	(0.00113)	(0.000847)	(0.00125)	(0.000771)
Number of observations	9316	9316	9316	9316	9316	9316	9316	9316
R^2	0.8859	0.8839	0.8917	0.7502	0.7918	0.7264	0.8336	0.7526

Notes: Specifications, coefficient estimates, and their statistical significances are shown. Standard errors are reported in parentheses under the coefficient estimates. Statistical significance level: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$. R^2, indicates the proportion of the variance for dependent variable explained by the independent variables of the model.

Discussion

We find that the ETS policy in China has significantly reduced carbon emissions. For each province-industry pair, the total carbon emissions yearly decrease by 8.139 million tons CO2eq on average and the carbon intensity decreases by 182.7 tons CO2eq/CNY. There also exists a significant difference in the reduction effects among regions and industries. The reduction effects of the ETS are obvious in Hubei, Chongqing, Shanghai, and Tianjin. The carbon emissions intensity of Hubei, Chongqing has plummeted. From the perspective of the industry, the implementation of the ETS has significantly reduced the total carbon emissions and carbon intensity of the power and high-carbon industries. Whereas the carbon emissions of emerging industries and traditional manufacturing industry are increasing under the ETS policy. Further, we explore the impact channels of the ETS policy from energy structure, energy consumption, and energy efficiency. Our findings suggest that the ETS policy reduces emissions primarily by lowering overall energy use and enhancing energy efficiency, whereas the energy structure channel has not contributed to emission reductions.

Following the policy recommendations put forward based on the results of the analysis: a. Considering the significant emission reduction effect of the ETS, to achieve the goal of carbon neutrality, China should further expand the regions and the scope of industries covered by carbon trading policy in the future; b. Since there are differences in policy impacts among regions and industries, the characteristics of different regions and industries should be taken into consideration for the further improvement of the policy. For instance, more details about emission quota allocation and transaction mechanisms could be set in a more specific way, c. The ETS policy reduces carbon emissions by decreasing the total energy consumption and the energy intensity while keeping the energy structure unchanged. Additionally, it has caused a decline in the share of renewable energy use. Therefore, the ETS policy should be preferably combined with other energy policies, particularly in the field of renewable energy, such as modest subsidies for renewable energy, d. The emerging manufacturing industry is the main direction in the process of industrial upgrading in the future. However, the ETS policy has not reduced the carbon emissions of the sector as a whole. The emerging manufacturing industry will further expand its scale, which needs us to reconsider the allocation of carbon quotas in this industry to avoid a rapid increase in carbon emissions in the future.

Methods

Data. Energy consumption and carbon emission data are derived from China Carbon Emission Accounts & Datasets (CEADs). In this paper, the data of 39 industrial categories in the data list of CEADs are grouped into 15 industries: Production and supply of electricity/thermal/gas and water, Building materials industry, Petrochemical industry, Smelting and pressing of metals, Processing of food/beverage and tobacco, Textile industry, Papermaking, Transportation equipment manufacturing, Information technology, Biomedicine, Electrical and mechanical equipment manufacturing, Metal products and equipment manufacturing, Mining, Waste resources utilization, and other manufacturing industries.

The data about the ETS POLICY comes from the list of major emission control enterprises published on the government websites of each pilot area. For example, the Beijing Ecological Environment Bureau, Tianjin Ecological Environment Bureau, Chongqing Ecological Environment Bureau, Shanghai Ecological Environment Bureau, Guangdong Province Ecological Environment Commission, Fujian Province Ecological Environment Bureau, and Hubei Province Ecological Environment Bureau.

The output value is from the provincial statistical yearbooks from 1999 to 2019, and the constant price is based on 2000 (the base period). The selected time interval is from 1999 to 2019.

Excluding the missing data, 30 provincial administrative regions and 15 industries are retained, with a total of 9,450 observations. The data structure is based on the province-industry-year three-dimensional observation.

Modelling approach. The Difference in Difference in Differences model (DDD) is applied in this paper to help us to investigate the carbon emission reduction effects and influence channels of the ETS policy. The baseline model is given as follows:

$$(1) \quad y_{ijt} = \propto + \beta D_{ijt} + \theta_{ij} + \delta_{jt} + \mu_{it} + \varepsilon_{ijt}$$

Where y is the explained variable, total carbon emissions, and its subscripts *i*, *j*, *and t* represent province, industry, and year. D_{ijt} is the core explanatory variable of the model. Only when *j* industry in *i* province has implemented the ETS policy in *t* year, the value is 1, otherwise is 0. θ_{ij} is a province-industry fixed effect, which eliminates the influence of the factors that do not change with time at the industry level of the province, such as the inherent characteristics of different industries in different provinces; $\delta_{jt}$is industry-year fixed effect, which captures time-varying and time-invariant industry characteristics, such as industry technology change, industry policy and etc. μ_{it} is the province-year fixed effect, which controls time-varying and time-invariant city characteristics, such as local public policy, business cycle etc., ε_{ijt} is the random disturbance term.

REFERENCE

Ackerman, Frank, and Elizabeth A. Stanton. 2012. “Climate Risks and Carbon Prices: Revising the Social Cost of Carbon.” *Economics* 6 (1). https://doi.org/10.5018/economics-ejournal.ja.2012-10.

Arlinghaus, Johanna. 2015. “Impacts of Carbon Prices on Indicators of Competitiveness: A Review of Empirical Findings.” Paris: OECD. https://doi.org/10.1787/5js37p21grzq-en.

Bayer, Patrick, and Michaël Aklin. 2020. “The European Union Emissions Trading System Reduced CO2 Emissions despite Low Prices.” *Proceedings of the National Academy of Sciences* 117 (16): 8804–12. https://doi.org/10.1073/pnas.1918128117.

Branger, Frédéric, Oskar Lecuyer, and Philippe Quirion. 2015. “The European Union Emissions Trading Scheme: Should We Throw the Flagship out with the Bathwater?” *WIREs Climate Change* 6 (1): 9–16. https://doi.org/10.1002/wcc.326.

Burtraw, Dallas, Karen L. Palmer, Ranjit Bharvirkar, and Anthony Paul, eds. 2001. *The Effect of Allowance Allocation on the Cost of Carbon Emission Trading*. Discussion Paper 01-30. https://doi.org/10.22004/ag.econ.10536.

Chan, Hei Sing (Ron), Shanjun Li, and Fan Zhang. 2013. “Firm Competitiveness and the European Union Emissions Trading Scheme.” *Energy Policy* 63 (December): 1056–64. https://doi.org/10.1016/j.enpol.2013.09.032.

Chen, Shuo, Anna Shi, and Xin Wang. 2020. “Carbon Emission Curbing Effects and Influencing Mechanisms of China’s Emission Trading Scheme: The Mediating Roles of Technique Effect, Composition Effect and Allocation Effect.” *Journal of Cleaner Production* 264 (August): 121700. https://doi.org/10.1016/j.jclepro.2020.121700.

Chen, Zhongfei, Xiao Zhang, and Fanglin Chen. 2021. “Do Carbon Emission Trading Schemes Stimulate Green Innovation in Enterprises? Evidence from China.” *Technological Forecasting and Social Change* 168 (July): 120744. https://doi.org/10.1016/j.techfore.2021.120744.

Clarkson, Peter M., Yue Li, Matthew Pinnuck, and Gordon D. Richardson. 2015. “The Valuation Relevance of Greenhouse Gas Emissions under the European Union Carbon Emissions Trading Scheme.” *European Accounting Review* 24 (3): 551–80. https://doi.org/10.1080/09638180.2014.927782.

Dechezleprêtre, Antoine, Daniel Nachtigall, and Frank Venmans. 2018. “The Joint Impact of the European Union Emissions Trading System on Carbon Emissions and Economic Performance.” Paris: OECD. https://doi.org/10.1787/4819b016-en.

Dijkstra, Bouwe R., Edward Manderson, and Tae-Yeoun Lee. 2011. “Extending the Sectoral Coverage of an International Emission Trading Scheme.” *Environmental and Resource Economics* 50 (2): 243–66. https://doi.org/10.1007/s10640-011-9470-1.

Dong, Feng, Yuanju Dai, Shengnan Zhang, Xiaoyun Zhang, and Ruyin Long. 2019. “Can a Carbon Emission Trading Scheme Generate the Porter Effect? Evidence from Pilot Areas in China.” *Science of The Total Environment* 653 (February): 565–77. https://doi.org/10.1016/j.scitotenv.2018.10.395.

Fu, Chun, Yuerong Huang, Yiwei Zheng, and Chuanyong Luo. 2022. “The Influence and Acting Pattern of China’s National Carbon Emission Trading Scheme on Regional Ecologicalization Efficiency of Industry.” *Scientific Reports* 12 (1): 11940. https://doi.org/10.1038/s41598-022-16185-4.

Godal, Odd, Yuri Ermoliev, and Ger Klaassen. n.d. “Carbon Trading with Imperfectly Observable Emissions,” 20.

Goulder, Lawrence H., Marc A. C. Hafstead, and Michael Dworsky. 2010. "Impacts of Alternative Emissions Allowance Allocation Methods under a Federal Cap-and-Trade Program." *Journal of Environmental Economics and Management* 60 (3): 161–81. https://doi.org/10.1016/j.jeem.2010.06.002.

Guo, Jianfeng, Fu Gu, Yinpeng Liu, Xi Liang, Jianlei Mo, and Ying Fan. 2020. "Assessing the Impact of ETS Trading Profit on Emission Abatements Based on Firm-Level Transactions." *Nature Communications* 11 (1): 2078. https://doi.org/10.1038/s41467-020-15996-1.

Haites, Erik. 2018. "Carbon Taxes and Greenhouse Gas Emissions Trading Systems: What Have We Learned?" *Climate Policy* 18 (8): 955–66. https://doi.org/10.1080/14693062.2018.1492897.

Hamamoto, Mitsutsugu. 2021. "Impact of the Saitama Prefecture Target-Setting Emissions Trading Program on the Adoption of Low-Carbon Technology." *Environmental Economics and Policy Studies* 23 (3): 501–15. https://doi.org/10.1007/s10018-020-00270-x.

Heiaas, Anne Marit. 2021. "The EU ETS and Aviation: Evaluating the Effectiveness of the EU Emission Trading System in Reducing Emissions from Air Travel." *Review of Business and Economics Studies*, no. 1: 84–120. https://cyberleninka.ru/article/n/the-eu-ets-and-aviation-evaluating-the-effectiveness-of-the-eu-emission-trading-system-in-reducing-emissions-from-air-travel.

Hovi, Jon, and Bjart Holtsmark. 2006. "Cap-and-Trade or Carbon Taxes? The Feasibility of Enforcement and the Effects of Non-Compliance." *International Environmental Agreements: Politics, Law and Economics* 6 (2): 137–55. https://doi.org/10.1007/s10784-006-9002-6.

Hu, Yucai, Shenggang Ren, Yangjie Wang, and Xiaohong Chen. 2020. "Can Carbon Emission Trading Scheme Achieve Energy Conservation and

Emission Reduction? Evidence from the Industrial Sector in China.” *Energy Economics* 85 (January): 104590. https://doi.org/10.1016/j.eneco.2019.104590.

Hua, Guowei, T.C.E. Cheng, and Shouyang Wang. 2011. “Managing Carbon Footprints in Inventory Management.” *International Journal of Production Economics* 132 (2): 178–85. https://doi.org/10.1016/j.ijpe.2011.03.024.

Huang, Zhonghua, and Xuejun Du. 2020. “Toward Green Development? Impact of the Carbon Emissions Trading System on Local Governments’ Land Supply in Energy-Intensive Industries in China.” *Science of The Total Environment* 738 (October): 139769. https://doi.org/10.1016/j.scitotenv.2020.139769.

Kim, Hyun Seok, and Won W. Koo. 2011. “Impacts of Regulating Greenhouse Gas Emissions on Livestock Trade Flows.” *Agricultural Economics* 42 (6): 679–84. https://doi.org/10.1111/j.1574-0862.2011.00541.x.

Kim, Man-Keun, and Taehoo Kim. 2016. “Estimating Impact of Regional Greenhouse Gas Initiative on Coal to Gas Switching Using Synthetic Control Methods.” *Energy Economics* 59 (September): 328–35. https://doi.org/10.1016/j.eneco.2016.08.019.

Kirat, Djamel, and Ibrahim Ahamada. 2011. “The Impact of the European Union Emission Trading Scheme on the Electricity-Generation Sector.” *Energy Economics* 33 (5): 995–1003. https://doi.org/10.1016/j.eneco.2011.01.012.

Klemetsen, Marit E., Knut Einar Rosendahl, and Anja Lund Jakobsen. 2016. “The Impacts of the EU ETS on Norwegian Plants’ Environmental and Economic Performance.” Working Paper 833. Discussion Papers. https://www.econstor.eu/handle/10419/192815.

Link, Christoph, Juliane Stark, Axel Sonntag, and Reinhard Hössinger. 2012. “Contribution of an Emission Trading Scheme to Reduce Road Traffic Induced CO2 Emissions in Austria.” *Procedia - Social and Behavioral Sciences* 48: 1971–82. https://doi.org/10.1016/j.sbspro.2012.06.1170.

Liu, Liwei, Chuxiang Chen, Yufei Zhao, and Erdong Zhao. 2015. “China′s Carbon-Emissions Trading: Overview, Challenges and Future.” *Renewable and Sustainable Energy Reviews* 49 (September): 254–66. https://doi.org/10.1016/j.rser.2015.04.076.

Liu, Meijuan, Chang Zhou, Feifei Lu, and Xiaohan Hu. 2021. “Impact of the Implementation of Carbon Emission Trading on Corporate Financial Performance: Evidence from Listed Companies in China.” Edited by Bing Xue. *PLOS ONE* 16 (7): e0253460. https://doi.org/10.1371/journal.pone.0253460.

Löfgren, Åsa, Dallas Burtraw, Markus Wråke, and Anna Malinovskaya. 2018. “Distribution of Emissions Allowances and the Use of Auction Revenues in the European Union Emissions Trading System.” *Review of Environmental Economics and Policy* 12 (2): 284–303. https://doi.org/10.1093/reep/rey012.

Long, Yilin, Yong Li, Yahui Wang, Yijia Cao, Lin Jiang, Yicheng Zhou, Youyue Deng, and Yosuke Nakanishi. 2022. “Low-Carbon Economic Dispatch Considering Integrated Demand Response and Multistep Carbon Trading for Multi-Energy Microgrid.” *Scientific Reports* 12 (1): 6218. https://doi.org/10.1038/s41598-022-10123-0.

Martin, Ralf, Mirabelle Muûls, and Ulrich J. Wagner. 2016. “The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years?” *Review of Environmental Economics and Policy* 10 (1): 129–48. https://doi.org/10.1093/reep/rev016.

Neuhoff, Karsten, Kim Keats Martinez, and Misato Sato. 2006. “Allocation, Incentives and Distortions: The Impact of EU ETS Emissions Allowance Allocations to the Electricity Sector.” *Climate Policy* 6 (1): 73–91. https://doi.org/10.1080/14693062.2006.9685589.

Qi, Shao-zhou, Chao-bo Zhou, Kai Li, and Si-yan Tang. 2021. "The Impact of a Carbon Trading Pilot Policy on the Low-Carbon International Competitiveness of Industry in China: An Empirical Analysis Based on a DDD Model." *Journal of Cleaner Production* 281 (January): 125361. https://doi.org/10.1016/j.jclepro.2020.125361.

Rickels, Wilfried, Alexander Proelß, Oliver Geden, Julian Burhenne, and Mathias Fridahl. 2021. "Integrating Carbon Dioxide Removal Into European Emissions Trading." *Frontiers in Climate* 3. https://www.frontiersin.org/articles/10.3389/fclim.2021.690023.

Rontard, Benjamin, and Humberto Reyes Hernández. 2022. "Political Construction of Carbon Pricing: Experience from New Zealand Emissions Trading Scheme." *Environmental Development* 43 (September): 100727. https://doi.org/10.1016/j.envdev.2022.100727.

Stavins, Robert N. 2008a. "A Meaningful U.S. Cap-and-Trade System to Address Climate Change." *Harvard Environmental Law Review* 32: 293. https://heinonline.org/HOL/Page?handle=hein.journals/helr32&id=297&div=&collection=.

———. 2008b. "Addressing Climate Change with a Comprehensive US Cap-and-Trade System." *Oxford Review of Economic Policy* 24 (2): 298–321. https://www.jstor.org/stable/23606646.

Tan, Ruipeng, and Boqiang Lin. 2022. "The Long Term Effects of Carbon Trading Markets in China: Evidence from Energy Intensive Industries." *Science of The Total Environment* 806 (February): 150311. https://doi.org/10.1016/j.scitotenv.2021.150311.

Tang, Kai, Yichun Liu, Di Zhou, and Yuan Qiu. 2021. "Urban Carbon Emission Intensity under Emission Trading System in a Developing Economy: Evidence from 273 Chinese Cities." *Environmental Science and Pollution Research* 28 (5): 5168–79. https://doi.org/10.1007/s11356-020-10785-1.

Taschini, Luca, Sascha Kollenberg, and Chris Duffy. 2014. “System Responsiveness and the European Union Emissions Trading System.” Monograph. London, UK: Centre for Climate Change Economics and Policy and Grantham Research Institute on Climate Change and the Environment. January 1, 2014. http://www2.lse.ac.uk/GranthamInstitute/Home.aspx.

Xuan, Dong, Xiaowei Ma, and Yuping Shang. 2020. “Can China’s Policy of Carbon Emission Trading Promote Carbon Emission Reduction?” *Journal of Cleaner Production* 270 (October): 122383. https://doi.org/10.1016/j.jclepro.2020.122383.

Yang, Xinyu, Ping Jiang, and Yao Pan. 2020. “Does China’s Carbon Emission Trading Policy Have an Employment Double Dividend and a Porter Effect?” *Energy Policy* 142 (July): 111492. https://doi.org/10.1016/j.enpol.2020.111492.

Zhang, Haijun, Maosheng Duan, and Zhe Deng. 2019. “Have China’s Pilot Emissions Trading Schemes Promoted Carbon Emission Reductions?– The Evidence from Industrial Sub-Sectors at the Provincial Level.” *Journal of Cleaner Production* 234 (October): 912–24. https://doi.org/10.1016/j.jclepro.2019.06.247.

Zhang, Wei, Jing Li, Guoxiang Li, and Shucen Guo. 2020. “Emission Reduction Effect and Carbon Market Efficiency of Carbon Emissions Trading Policy in China.” *Energy* 196 (April): 117117. https://doi.org/10.1016/j.energy.2020.117117.

Zhou, Bo, Cheng Zhang, Haiying Song, and Qunwei Wang. 2019. “How Does Emission Trading Reduce China’s Carbon Intensity? An Exploration Using a Decomposition and Difference-in-Differences Approach.” *Science of the Total Environment,* 10.

Zhu, Junming, Yichun Fan, Xinghua Deng, and Lan Xue. 2019. "Low-Carbon Innovation Induced by Emissions Trading in China." *Nature Communications* 10 (1): 4088. https://doi.org/10.1038/s41467-019-12213-6.